COMPARISON OF SYNOPTIC SCALE WAVE DISTURBANCES IN THE TROPICAL WESTERN PACIFIC OCEAN BETWEEN 1972 AND 1973.

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THESIS

COMPARISON OF SYNOPTIC SCALE WAVE DISTURBANCES IN THE TROPICAL WESTERN PACIFIC OCEAN BETWEEN 1972 AND 1973

by

Charles Robert Miller, III

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Thesis Advisor: C.-P. Chang

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The structure and properties of the tropical easterly waves have been found to vary considerably between different regimes and time periods. This study investigates the possible roles played by the long-term sea-surface temperature (SST) variations in the upstream region on the waves. Time series of tropical western Pacific radiosonde data during two contrasting 8-month periods of SST anomalies, May-December 1972, which has abnormally high SST in the central and eastern Pacific, and May-December 1973 which has below normal

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Comparison of Synoptic Scale Wave
Disturbances in the Tropical Western
Pacific Ocean Between 1972 and 1973

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ABSTRACT

The structure and properties of the tropical easterly waves have been found to vary considerably between different regimes and time periods. This study investigates the possible roles played by the long-term sea-surface temperature (SST) variations in the upstream region on the waves. Time series of tropical western Pacific radiosonde data during two contrasting 8-month periods of SST anomalies, May-December 1972, which has abnormally high SST in the central and eastern Pacific, and May-December 1973 which has below normal SST in the same region are analyzed. In both periods, the waves have the same periodicity of 4-5 days and a zonal wavelength on the order of 3500 km, but the vertical phase and amplitude distributions are different as well as the thermal structures. The results suggest that SST influences the waves in two ways: 1) direct effect, the warmer SST favors a better-defined warm core structure which increases the lower tropospheric wave amplitude; and 2) indirect effect, the variation of SST changes the large-scale mean wind circulation which, in turn, changes the vertical structure and upper tropospheric amplitude of the waves.

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I. INTRODUCTION

Recent studies on synoptic-scale tropical wave disturbances have modified some of the earlier wave models such as those of Riehl (1945, 1954) and Palmer (1952). These studies (Yanai, et al, 1968; Nitta and Yanai, 1969; Wallace and Chang, 1969; Chang, et al, 1970; Nitta, 1970, Chang, 1970; Wallace, 1971; Reed and Recker, 1971; Burpee, 1972, 1974; Reed and Johnson, 1974; Neiva, 1974; and others), which used primarily the spectrum and/or composite analysis of time series from radiosonde and/or satellite data, are based on many layer data samples as compared to the map analysis of the earlier investigations. There are some conclusive agreements among these studies, such as the 4 to 5 day periodicity and the westward zonal propagation direction. However, quite different results also exist on the wave structure between different studies. The most noticeable discrepancies may be summarized as follows:

1. The vertical phase structure. Studies by Yanai et al (1968), as well as the earlier easterly wave model by Riehl (1954), indicate a significant eastward tilt of the waves in the lower and middle troposphere; while Wallace and Chang (1970), Chang et al (1970) and Wallace (1971) found most of the waves to have very little vertical tilt and some of the waves may even tilt westward with height.

2. The thermal structure. Many earlier models suggest that the waves are cold core in nature while more recent studies have indicated a warm core structure in the middle-upper troposphere.

3. The horizontal wavelength. Early map analysis studies give a zonal wavelength of 1500-2000 km. More recently, Yanai, et al (1968) found a wavelength of 6000-8000 km while Wallace and Chang and Chang, et al found a wavelength of 3000-4000 km in their studies.

These discrepancies have been discussed by Wallace (1971) and others. The proposed explanation to date emphasizes the difference of geographical locations and time periods. For example, the eastern and central Pacific data tend to suggest more eastward phase tilting with height and longer zonal wavelengths than the western Pacific data. The possibility of the existence of two or more types of waves with their relative strength varying from year to year is also mentioned. However, very little physical reasoning has been offered to explain how and why these geographical and annual variations occur with the exception of Holton's (1971) diagnostic numerical model which attributes the different vertical structure to different vertical profiles of time-mean winds.

The effects of long-term and geographical variations of sea-surface temperatures (SST) on long-period, planetary-scale atmospheric circulations have been noticed by several authors. Bjerknes (1969) has proposed a relationship between the zonal migration of the Walker Circulation over the equatorial Pacific and the SST variations. Kruger and Winston (1974) and Namias (1974) have also identified large-scale circulation fluctuations with the influence of SST changes. Since most of the tropical waves studied earlier were over oceanic regions, it may be interesting to examine whether SST variations account for part of the observed differences in wave structure and properties.

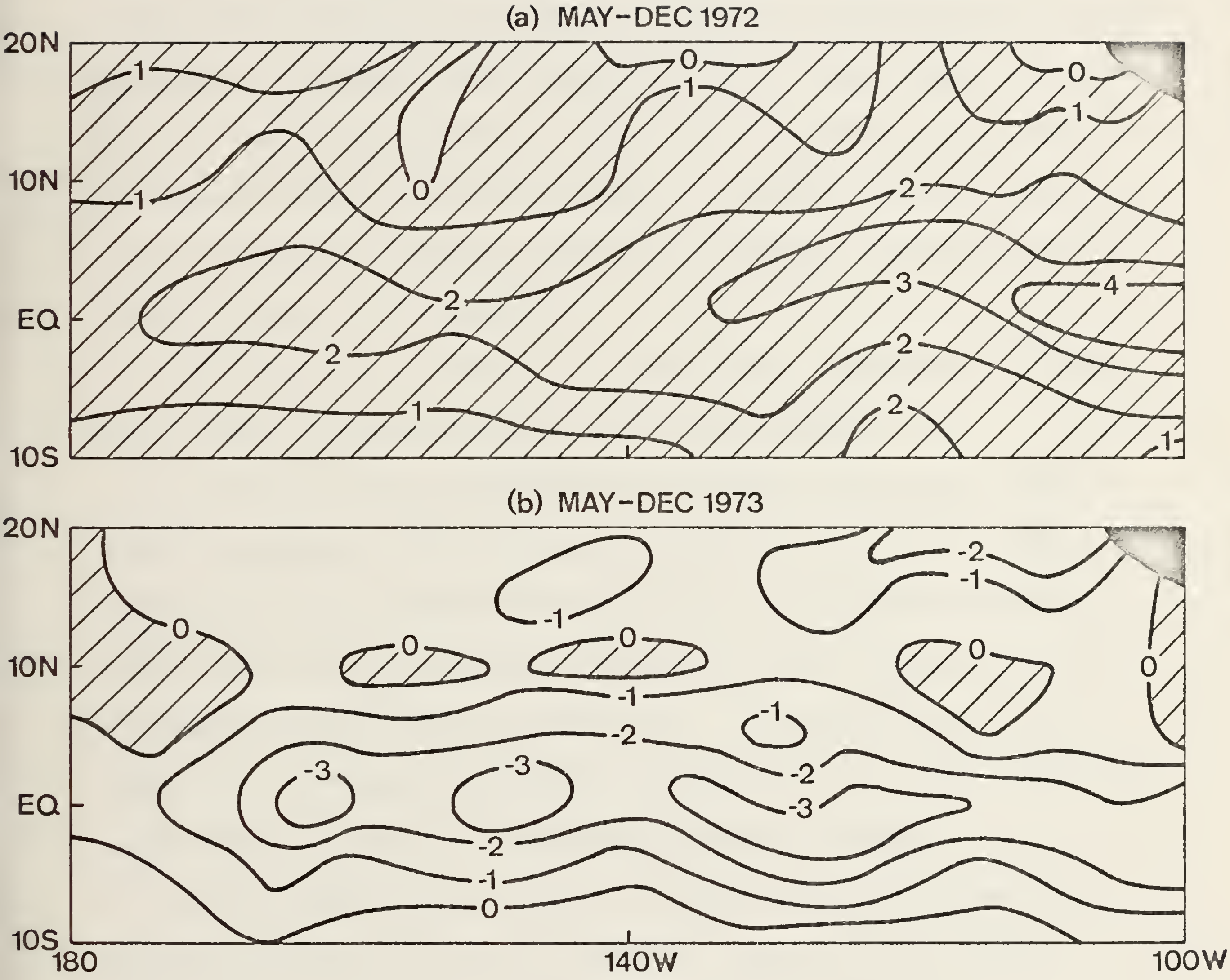


Figure 1. Mean sea surface temperature anomalies over the eastern Pacific Ocean for May-December 1972, (a), and May-December 1973, (b).

The purpose of this study is to analyze the tropical western Pacific radiosonde data over two different periods, the last eight months of 1972 and 1973, during which large SST anomalies have been noticed, at least in the eastern Pacific region. Since the waves generally propagate westward it is hoped to find out what effects, if any, these variations in SST in the eastern Pacific may have on the structure of the waves in the western Pacific. These two years were selected for this study also because of complete satellite coverage. Hopefully, the satellite data will be analyzed at a later date.

The rationale for studying the relationships between SST and atmospheric waves is primarily based on two observations:

1. The waves have been observed to possess a warm core in the middle troposphere, which implies that latent heating due to cumulus convection may be an important energy source. Cumulus convection is closely controlled by low-level equivalent potential temperature, so the effect of SST is obviously important. On the other hand, if no substantial differences between the two SST periods is found, important implications for the wave energetics may also be deduced.

2. The change in SST is known to affect the planetary-scale circulation in which the waves are imbedded. Thus the waves may be influenced by SST through the variations in the basic flow.

In this study the results of data analysis will be examined in light of the above considerations.

II. DATA

The study was initially planned to include radiosonde data from 11 tropical western Pacific stations; however, only data from seven stations were available from the National Weather Records Center at Asheville, North Carolina for the periods of interest. Only six of these stations were found to have a reasonably sufficient number of reports to allow the use of spectrum analysis. These stations are shown in Fig. 2. Twice-daily reports were available at Johnston Island for both years and at Majuro, Ponape, Truk and Koror for 1972, while only once-daily reports were available at Yap for both years and at Majuro, Ponape, Truk, and Koror for 1973.

For these six stations time series were generated for temperature, zonal and meridional wind components at 13 levels: 1000, 850, 700, 600, 500, 400, 300, 250, 200, 175, 150, 125, and for the relative humidity at the six lowest levels. Missing data, which are always less than ~5% of the total series, were linearly interpolated in time. No gap larger than two or three days exists at any of the stations except Johnston Island where the period 19-27 August 1972 was missing. Data at the lower levels was more complete than at the upper levels.

In order to remove long-term trends an 89-point Gaussian high-pass filter designed by Holloway (1958) was used. This filter with a standard deviation of 8.33, reduces the number of data points from 490 to 404 causing 22 days to be lost from either end of each time series. The response function of the filter was such that for periods less than or

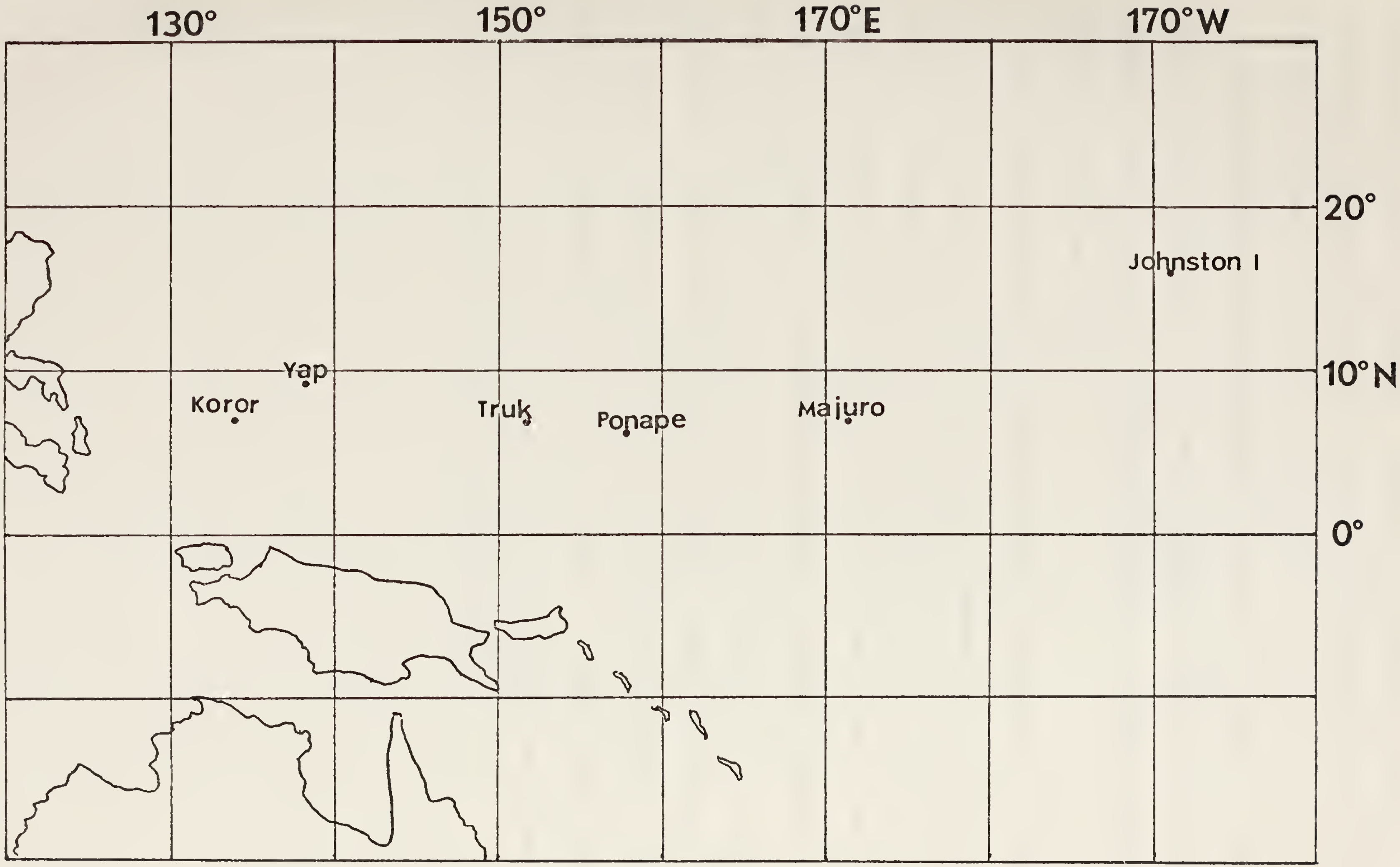


Figure 2. Radiosonde stations used in this study.

equal to 20 days the response is equal to or greater than 95%. The filter has no significant effect on disturbances having the range of periods with which the study is concerned.

The spectrum and cross-spectrum analysis was performed on the IBM 360 computer at the W. R. Church Computer Center of the Naval Postgraduate School utilizing the BMD02T program of the UCLA Biomedical Statistical Program Package.

The significance of the spectral results was tested for each power spectrum distribution using a procedure recommended by Mitchell, et al (1966). All power spectra are subjected to a test of the 95% confidence levels (shown as dashed curves in Figs. 3, 4 and 5) which was based on the null hypothesis of simple persistence. Confidence limits for the coherence estimates were also established utilizing a table prepared by Mitchell (1966) based on data compiled by Amos and Koopmans (1963). The table is entered with the number of degrees of freedom of the coherence estimates given by 1.25 N/m where N is the number of data points and m is the number of lags. For this study N was equal to 404 and m was chosen as 50 giving a 25 day lag period.

JOHNSTON 72 V

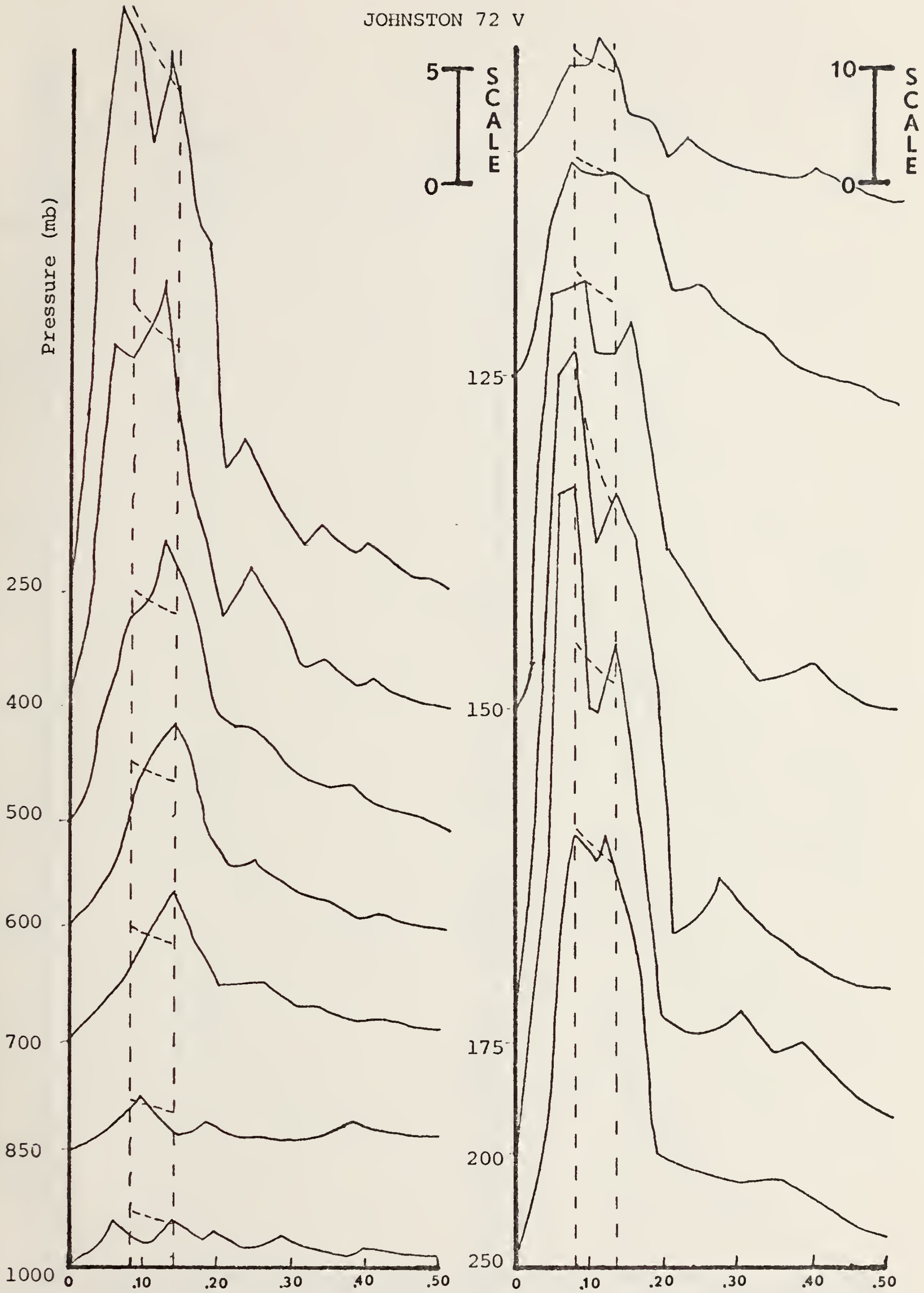


Figure 3(a). Power spectra ($m^2 sec^{-2}$ per $2\pi/50$ day^{-1}) at each of the 13 levels for Johnston during the 1972 season. The 95% confidence limit (dashed line) is plotted in the .18-.24 frequency band.

MAJURO 72 V

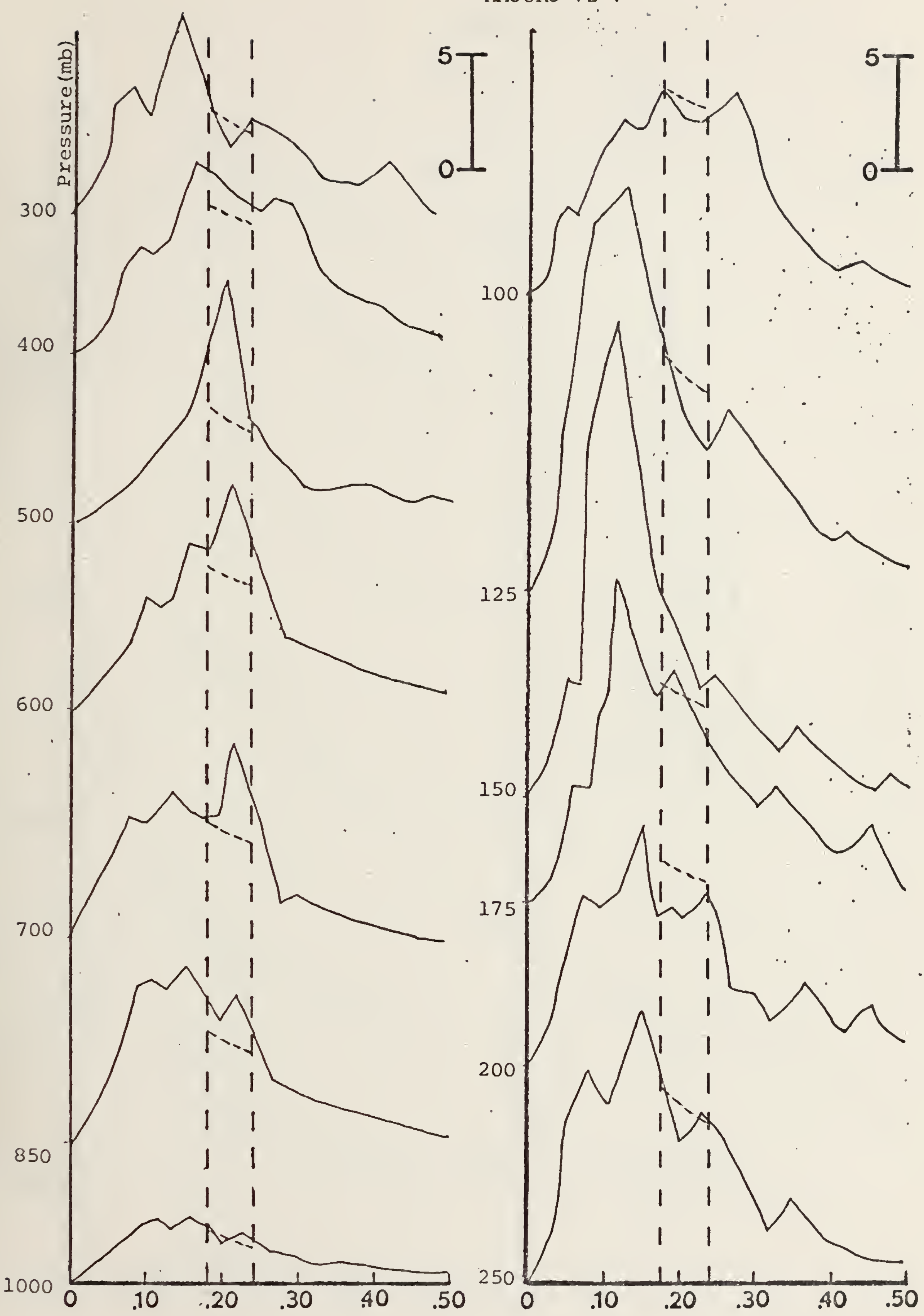


Figure 3(b). Same as Fig. 3(a), except for Majuro.

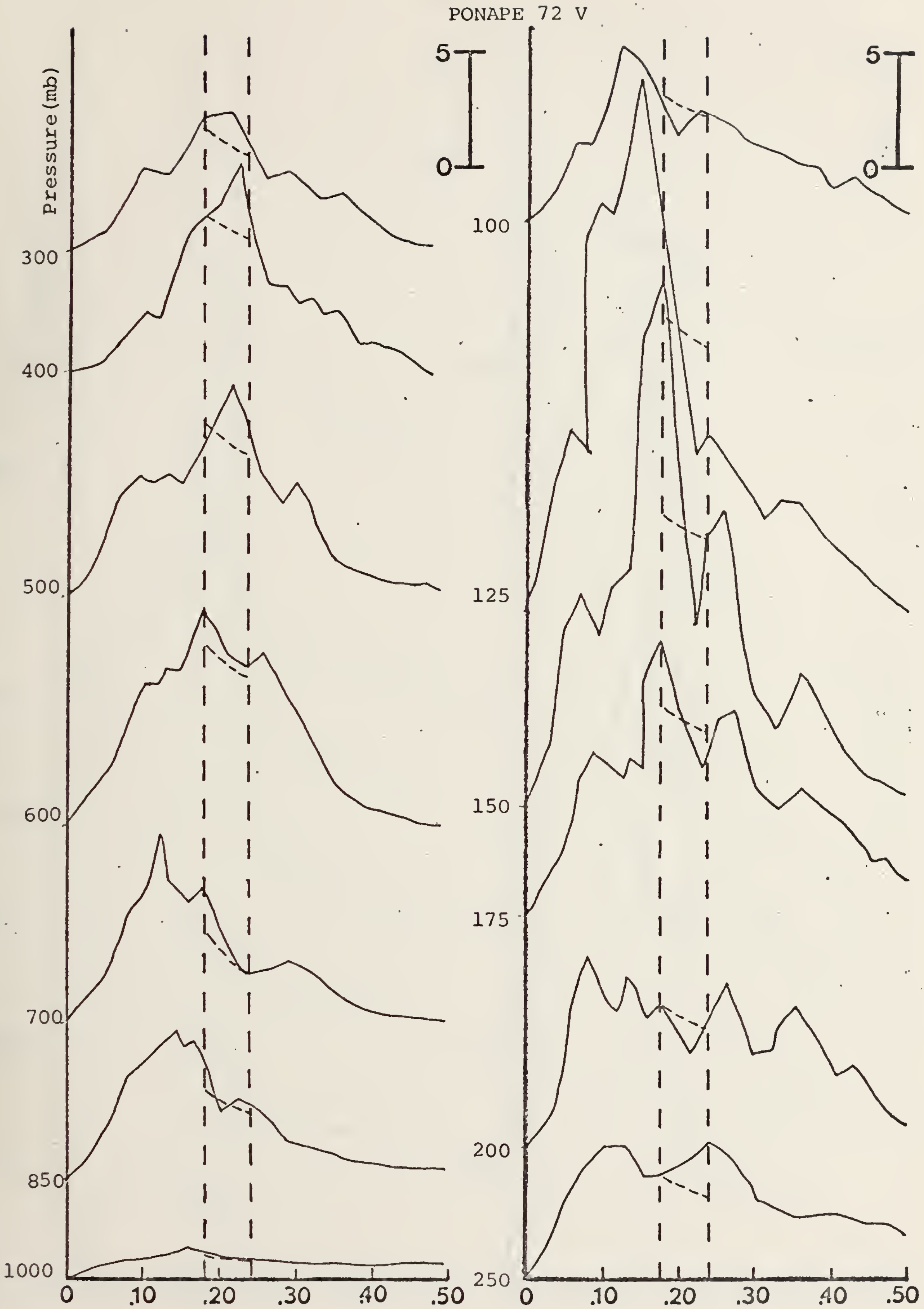


Figure 3(c). Same as Fig. 3(a), except for Ponape.

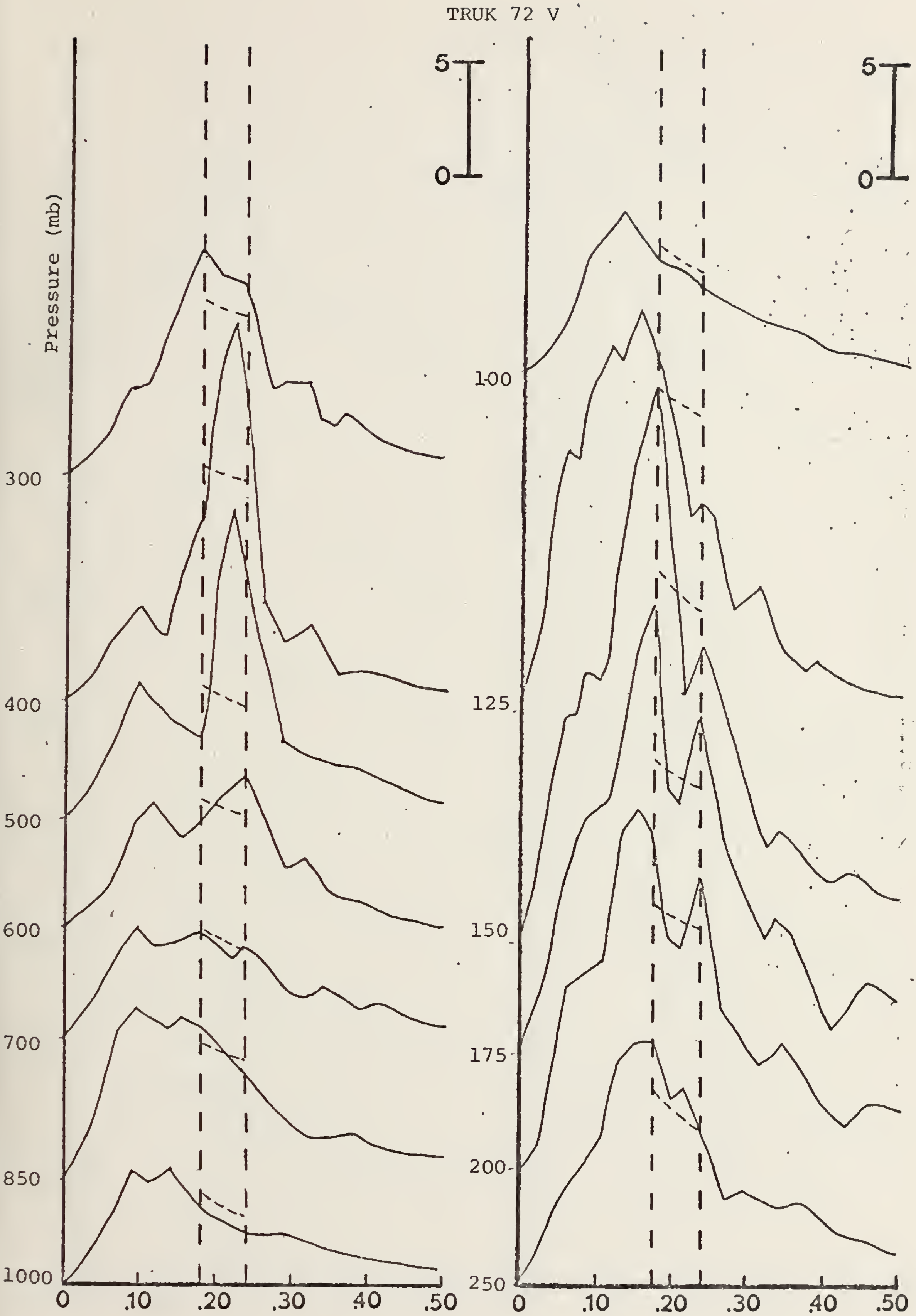


Figure 3(d). Same as Fig. 3(a), except for Truk.

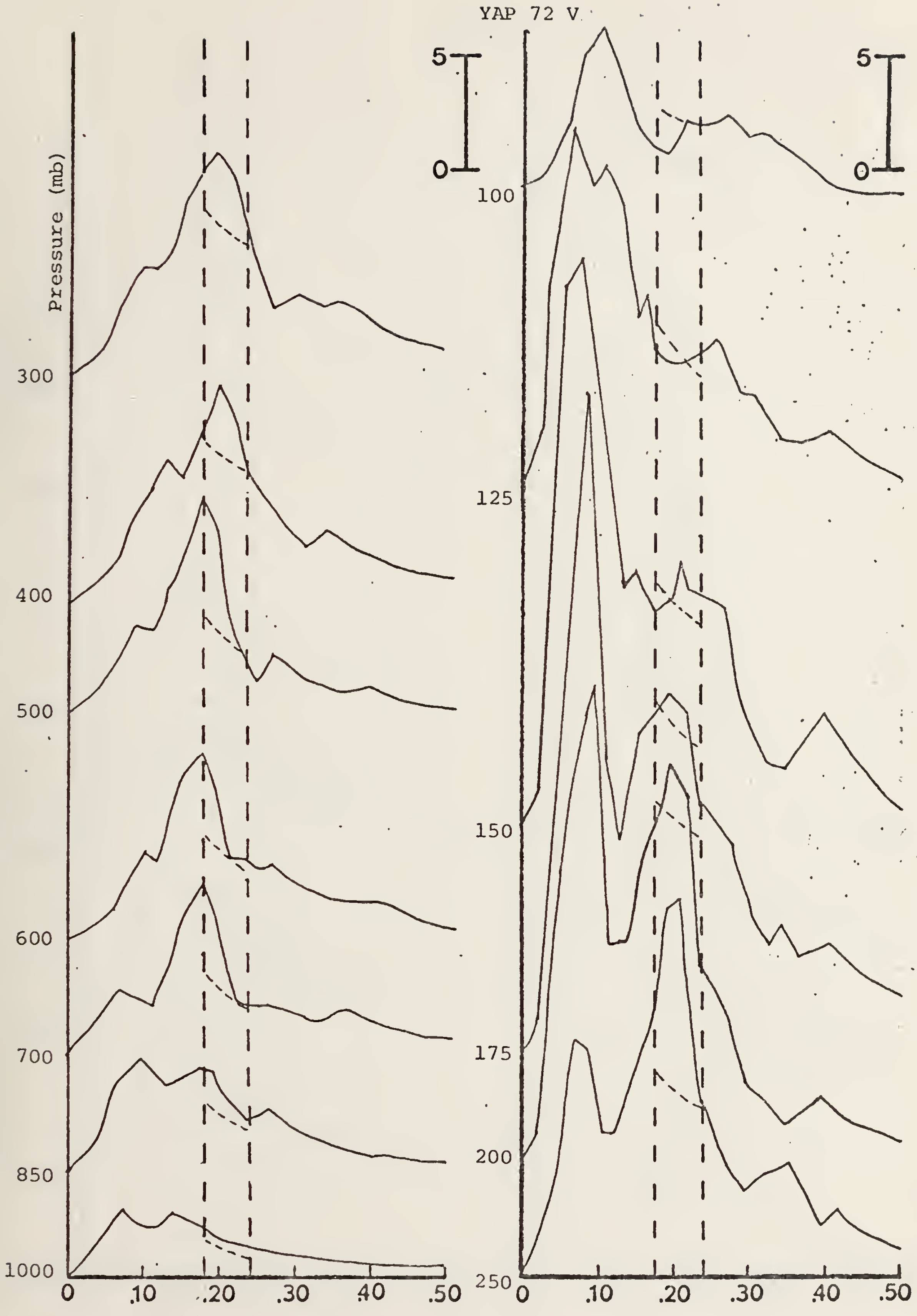


Figure 3(e). Same as Fig. 3(a), except for Yap.

Figure 3(f). Same as Fig. 3(a), except for Koror.

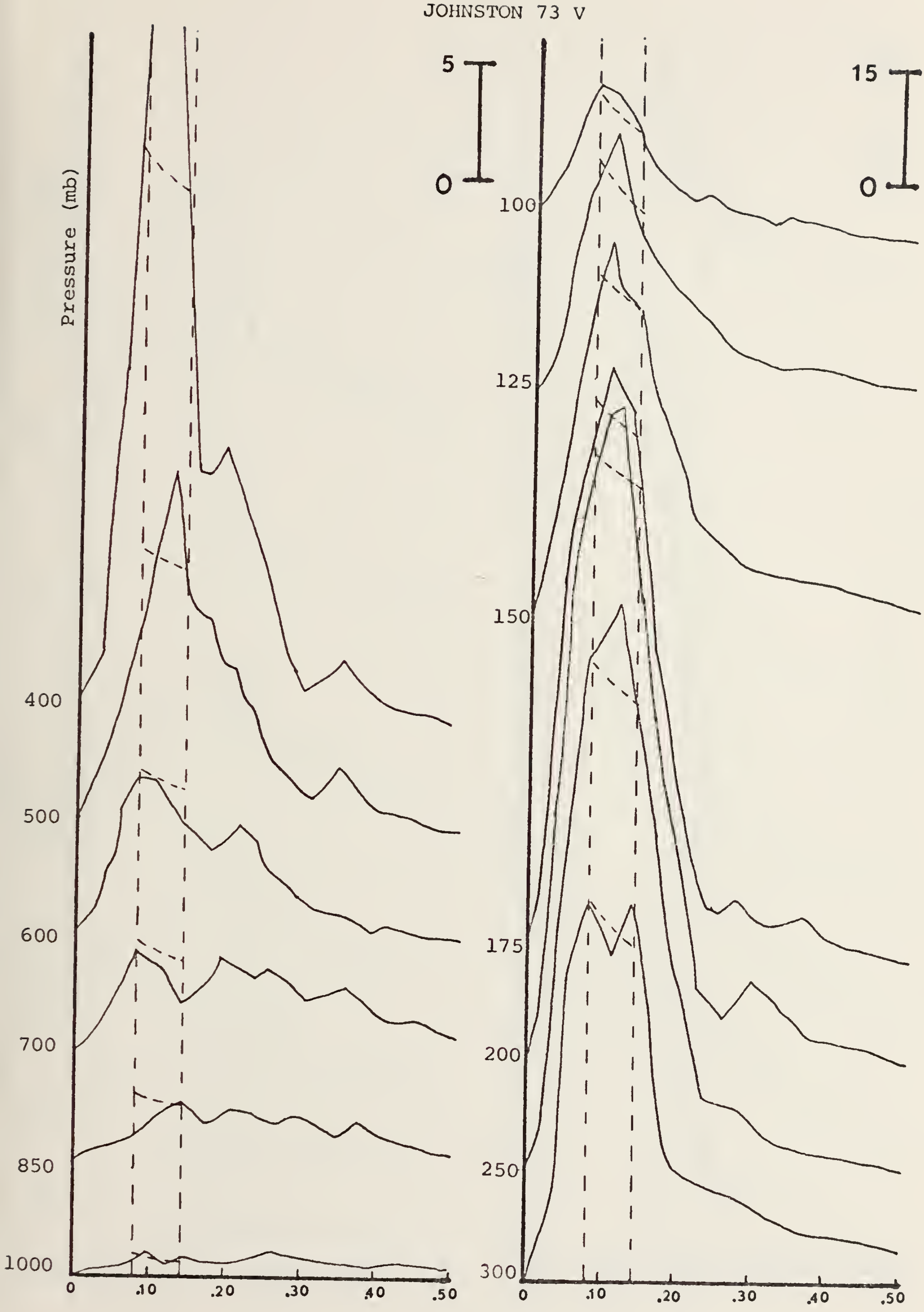


Figure 4(a). Power spectra ($m^2 sec^{-2}$ per $2\pi/50$ day^{-1}) at each of the 13 levels for Johnston during the 1973 season. The 95% confidence limit (dashed line) is plotted in the bands of interest.

MAJURO 73 V

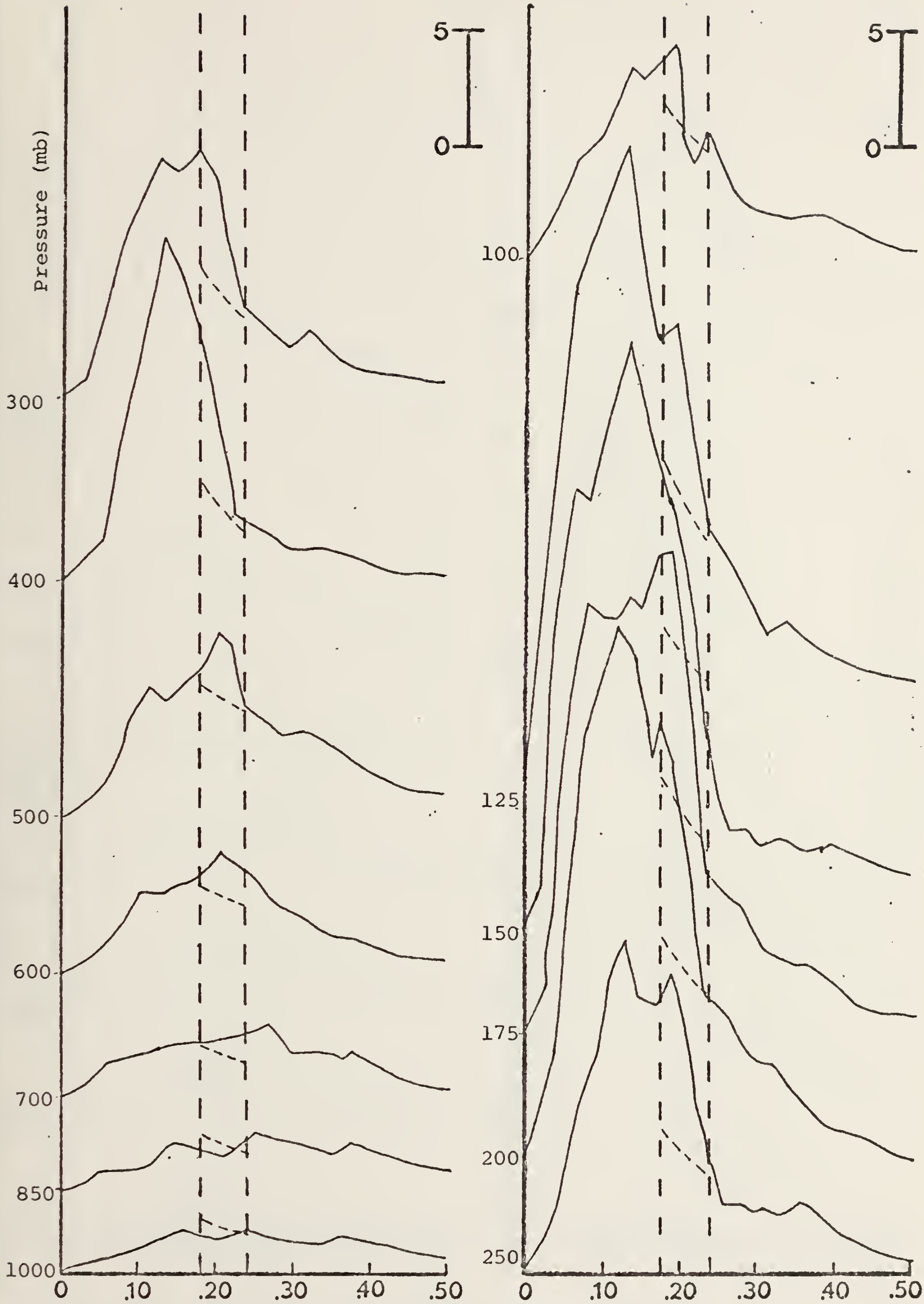


Figure 4(b). Same as Fig. 4(a), except for Majuro.

PONAPE 73 V

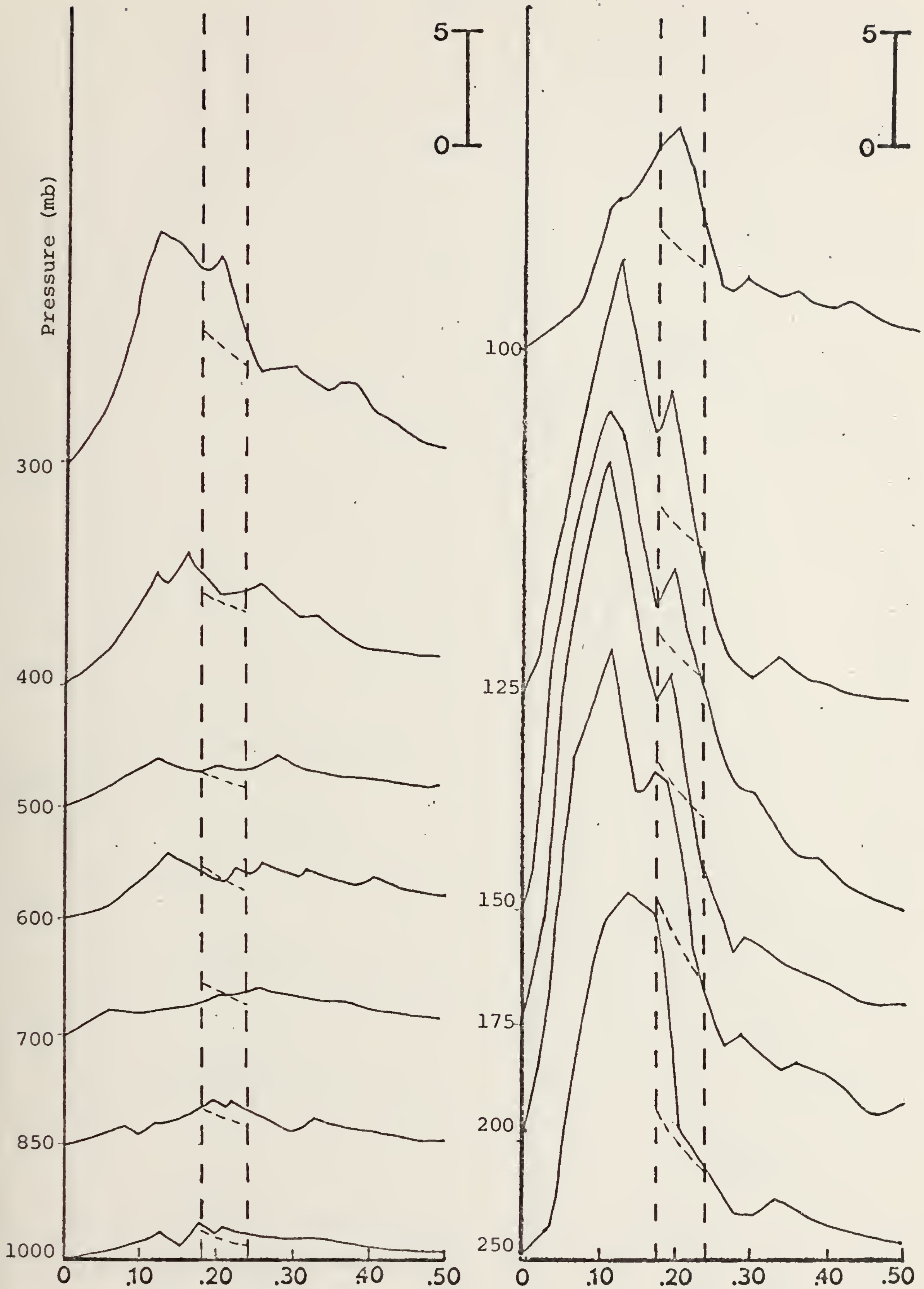


Figure 4(c). Same as Fig. 4(a), except for Ponape.

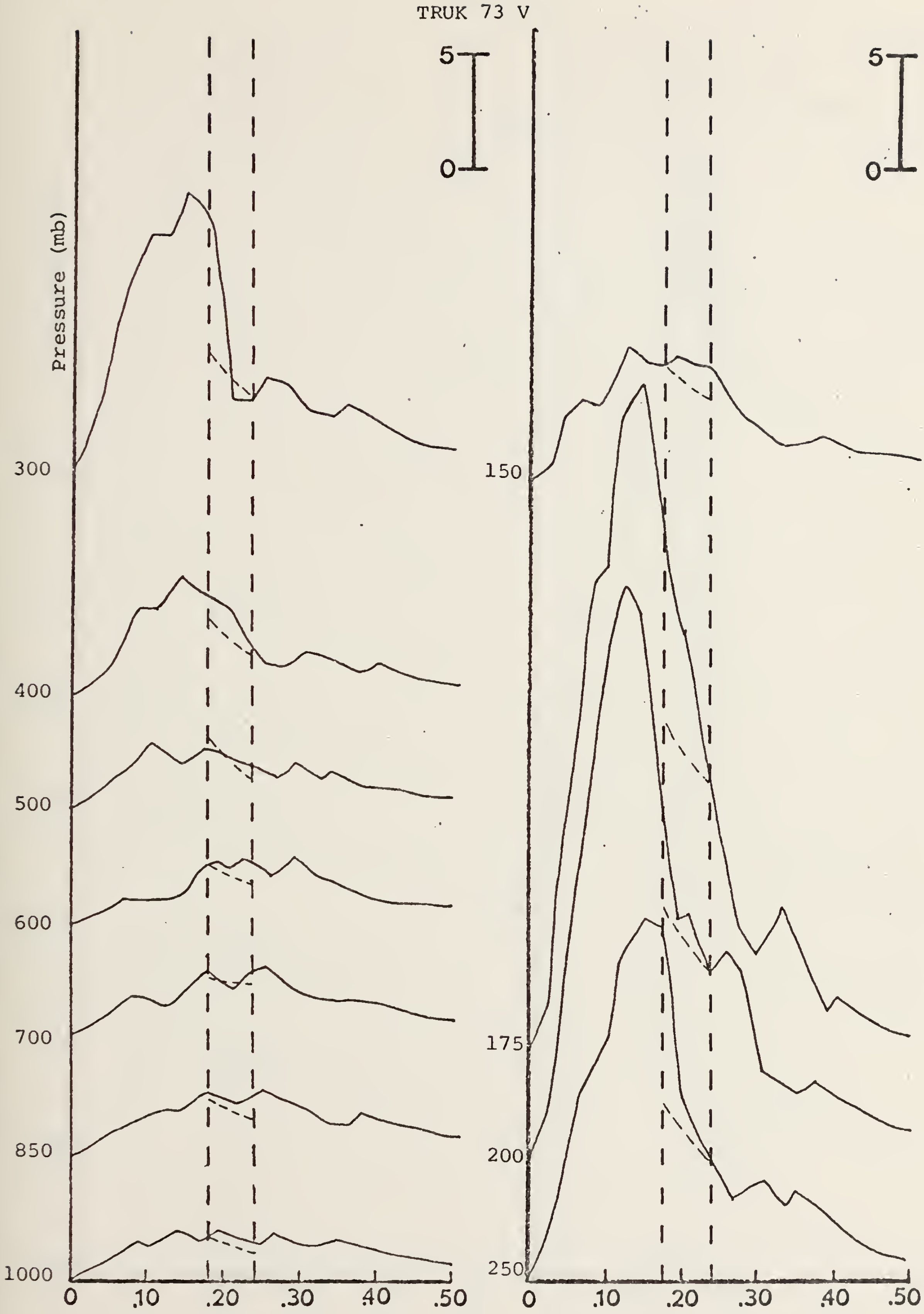


Figure 4(d). Same as Fig. 4(a), except for Truk.

YAP 73 V

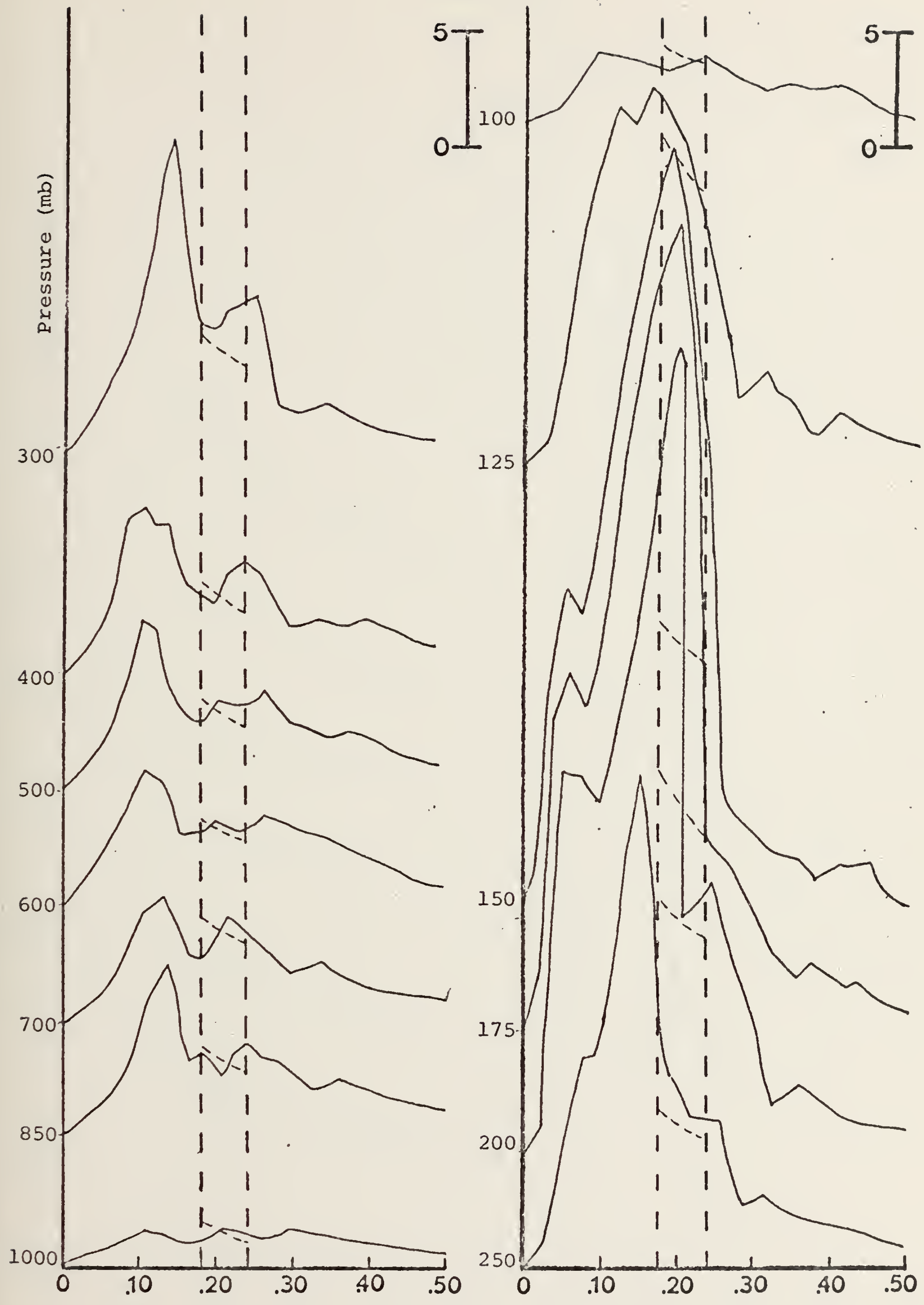


Figure 4(e). Same as Fig. 4(a), except for Yap.

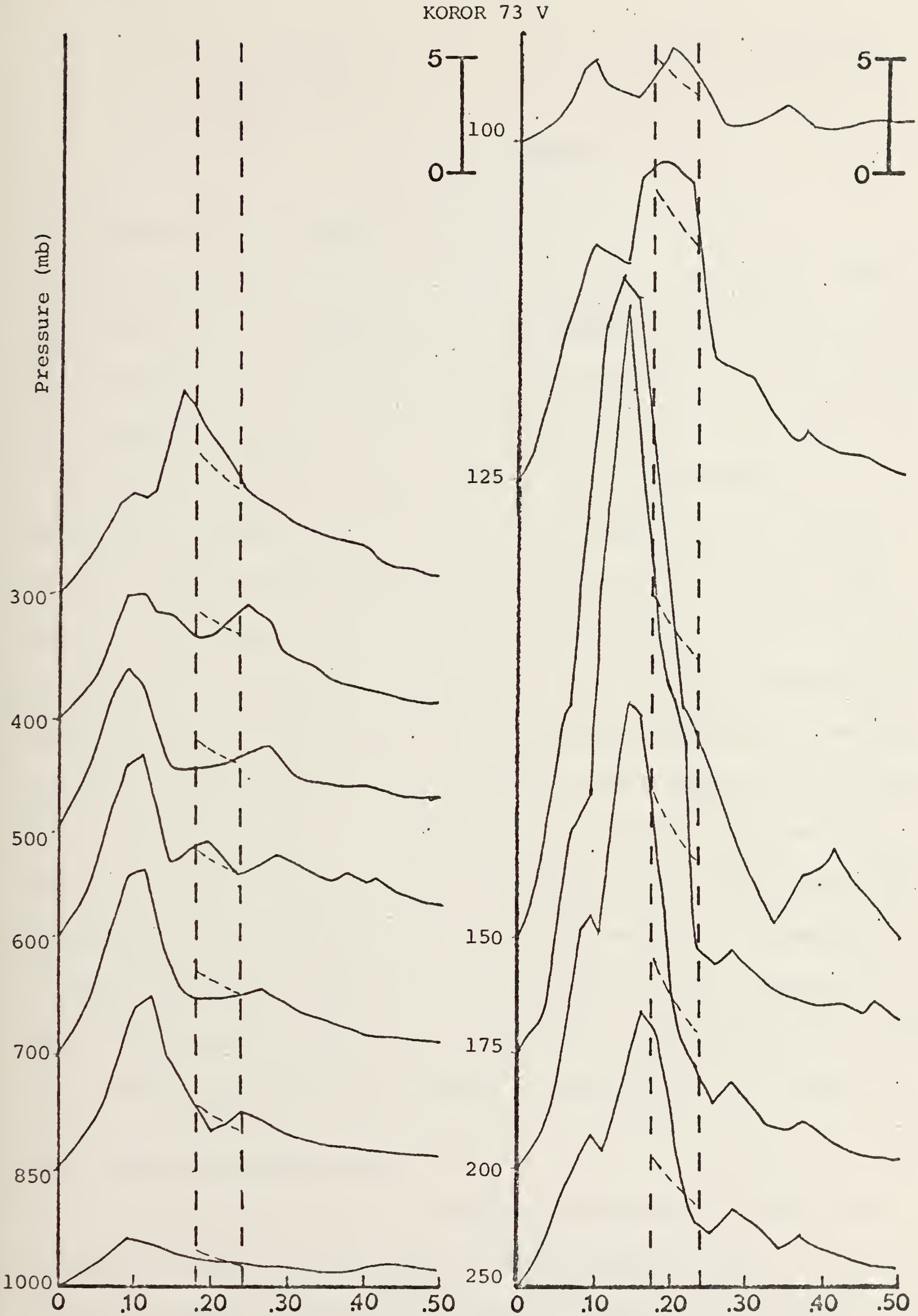


Figure 4(f). Same as Fig. 4(a), except for Koror.

III. RESULTS

A. POWER SPECTRA OF INDIVIDUAL LEVELS

Power spectral estimates for each of the four parameters, temperature, zonal (u) and meridional (v) wind components and relative humidity were plotted at each of the 13 levels for both years at all six stations. The v-spectra at lower levels generally show a significant peak in the 0.18-0.24 cycle per day (cpd) frequency band, corresponding to a periodicity of approximately 4 to 5 days, except those at Johnston Island. This 4-5 day periodicity will be the main interest of this study. The u-spectra are generally less distinct in both years. All v-spectra are presented in Figs. 3 and 4, with the 95% confidence level indicated only for the 0.18-0.24 cpd frequency band which is the band chosen for further study at all stations (except Johnston Island) and all levels for reasons of consistency. At Johnston Island which is well to the east and north of the five other stations the significant v-spectral peaks are close to the 0.10 cpd frequency, or a period of 10 days. This was found to be the case with the other parameters as well but they were somewhat less pronounced. The frequency band selected for further study at Johnston Island is therefore 0.08-0.14 cpd.

B. INTER-LEVEL CROSS SPECTRA

The vertical structure of the wind oscillations for the 4-5 day periodicity was first determined by cross-spectral analysis between levels. The 700 mb and 200 mb levels were used as the reference levels

at each station. The average coherence squares and phase differences between the other levels and the base levels for the 0.18 - 0.24 cpd (0.08-0.14 cpd for Johnston Island) were computed. When the smoothing of the spectral estimates was considered it was found that the degrees of freedom for the combined estimates was ~25, resulting in coherence squares with 95% confidence levels if they are greater than or equal to 0.11. Tables I-VI show the results of these computations. The stations are arranged according to longitude with the easternmost stations at the top. Positive phase values indicate that the base series leads the other series by the portion of the cycle listed. Table I for the 1972 v-component shows that at most stations the lower levels tend to be out of phase with the upper levels. At every station with the 4-5 day periodicity there is an abrupt phase shift near 300-400 mb levels, while the levels above and below this demarcation show very little tilt among themselves. At Johnston Island the 10 day waves are nearly in phase at all levels.

Table IV, for the 1973 v-component again shows a vertical structure with virtually no phase difference between the upper and lower levels for the 10-day fluctuations at Johnston Island. Examination of the phase relationships at the other stations, however, reveals a general systematic tilt in the vertical. This is very apparent at Majuro where there is a consistent tilt to about 200 mb with the low levels leading the upper levels, implying upward phase propagation. At Ponape there is little tilt below 700 mb but a systematic upward propagation from 700 to 250 mb. At Truk there is again an upward phase propagation throughout the troposphere. At Yap there is no tilt in the layer below 600 mb, but a consistent tilt between 600 and 300 mb with the waves propagating

TABLE I. Inter-level cross spectra for 1972 season.

a. Coherence square between v at 700 mb (top), 200 mb (bottom) and other levels for the .18-.24 cycle day^{-1} frequency bands. (Significance level $\geq$ 95% if coherence square $\geq$ .11.)

Level (mb)

Station	1000	850	700	600	500	400	300	250	200	175	150	125	100
Johnston	41	40	100	75	63	47	48	38	37	32	28	31	37
Majuro	56	77	100	80	63	47	17	08	16	20	24	06	20
Ponape	43	52	100	83	62	34	17	06	10	13	22	27	08
Truk	37	70	100	69	32	32	08	06	15	18	22	12	09
Yap	48	25	100	75	46	15	14	21	32	28	21	07	07
Koror	25	62	100	75	45	23	04	05	10	15	09	06	05
Johnston	26	16	37	38	50	56	62	87	100	91	72	59	44
Majuro	18	21	16	13	08	04	19	61	100	85	54	20	15
Ponape	11	13	10	06	04	03	30	63	100	80	54	27	07
Truk	08	13	15	09	04	11	32	66	100	87	53	25	02
Yap	28	16	32	20	09	14	52	78	100	88	58	07	02
Koror	16	07	10	11	12	07	28	69	100	80	44	11	07

TABLE I. Inter-level cross spectra for 1972 season.

b. Phase difference (in cycles) between v at 700 mb (top) and 200 mb (bottom) and other levels for the 0.18-0.24 cycle day^{-1} frequency bands. (Positive values indicate that the base series leads other series.)

	Level (mb)												
Station	1000	850	700	600	500	400	300	250	200	175	150	125	100
Johnston	05	00	00	03	02	05	09	05	05	03	00	00	05
Majuro	00	00	00	00	-03	00	-03	-	-30	-31	-35	-	15
Ponape	-02	-03	00	-03	-07	-11	-14	-	-	-45	-45	-49	-
Truk	05	04	00	-05	-09	-09	-	-	43	44	46	40	-
Yap	00	05	00	-04	-05	-07	-34	-38	-45	-45	50	-	-
Koror	-04	-03	00	-03	-07	-09	-	-	-	47	-	-	-
Johnston	00	-10	-05	00	00	04	05	00	00	00	00	00	03
Majuro	25	30	30	30	-	-	-10	00	00	00	-02	-10	-35
Ponape	29	-45	-	-	-	-	03	00	00	-03	00	-05	-
Truk	-	50	-03	-	-	-25	-06	00	00	00	00	-06	-
Yap	39	40	45	38	-	09	04	02	00	00	00	-	-
Koror	41	-	-	-46	-45	-	04	03	00	-01	00	13	-

TABLE II. Same as Table 1, except for u, 1972.

a. Coherence squares

Station	1000	850	700	600	500	400	300	250	200	175	150	125	100
						Level (mb)							
Johnston	20	41	100	69	48	20	10	08	10	10	16	23	27
Majuro	23	42	100	61	28	15	05	03	04	04	08	09	20
Ponape	26	60	100	75	57	22	28	27	15	11	12	05	09
Truk	27	46	100	62	44	34	14	08	06	05	06	09	17
Yap	04	34	100	49	05	16	07	09	10	10	12	07	14
Koror	06	29	100	51	14	02	05	03	11	16	16	06	07
Johnston	15	06	10	09	26	54	59	86	100	93	86	69	38
Majuro	08	04	04	07	05	08	43	73	100	71	21	10	01
Ponape	07	13	15	15	19	18	57	69	100	84	55	17	15
Truk	01	05	06	11	23	30	71	79	100	67	44	25	04
Yap	03	08	10	19	08	16	62	67	100	85	31	29	06
Koror	12	08		13	20	21	27	59	100	75	25	17	26

TABLE II. Same as Table I, except for u, 1972.

b. Phase difference — Level (mb)

Station	1000	850	700	600	500	400	300	250	200	175	150	125	100
Johnston	04	00	00	-03	-03	00	-	-	-	-	-12	-13	-06
Majuro	00	00	00	00	07	09	-	-	-	-	-	-	00
Ponape	-15	-04	00	-02	-07	-07	-07	-06	-16	-18	-14	-	-
Truk	00	00	00	00	-05	-03	-04	-	-	-	-	-	-03
Yap	-	05	00	00	-	-24	-	-	-	-	-05	-	-17
Koror	-	02	00	-04	-05	-	-	-	-17	-24	-27	-	-
Johnston	17	-	-	-	03	03	00	00	00	00	00	00	00
Majuro	-	-	-	-	-	-	03	03	00	00	00	-	-
Ponape	-	00	16	21	17	15	02	00	00	-01	-04	-03	-68
Truk	-	-	-	06	08	00	00	00	00	00	-03	-04	-
Yap	-	-	-	00	-	-09	-02	00	00	00	-05	00	-
Koror	-24	-	17	24	05	07	00	00	00	-04	-06	-06	12

TABLE III. Same as Table I, except for T, 1972.

a. Coherence squares

	Level (mb)												
Station	1000	850	700	600	500	400	300	250	200	175	150	125	100
Johnston	20	07	100	11	07	07	12	08	06	05	05	18	22
Majuro	33	07	100	46	09	13	12	06	13	02	08	08	18
Ponape	26	12	100	14	07	12	13	15	22	16	18	07	04
Truk	32	09	100	34	06	09	18	06	06	18	21	27	07
Yap	28	22	100	40	04	13	03	08	05	13	17	16	05
Koror	10	29	100	26	27	07	04	13	07	15	17	13	07
Johnston	14	07	06	05	05	10	14	48	100	59	11	22	10
Majuro	13	03	13	25	26	14	39	40	100	35	10	22	14
Ponape	06	15	22	17	09	11	18	23	100	28	08	13	08
Truk	11	06	06	09	04	04	19	07	100	42	23	13	19
Yap	02	09	05	05	17	07	23	29	100	23	07	17	14
Koror	03	07	07	18	15	17	14	13	100	16	05	08	08

TABLE III. Same as Table I, except for T, 1972.

b. Phase difference	Level (mb)												
Station	1000	850	700	600	500	400	300	250	200	175	150	125	100
Johnston	-05	-	00	00	-	-	15	-	-	-	-	-48	-34
Majuro	-04	-	00	-03	-	10	14	-	17	-	-	-	-38
Ponape	02	00	00	-16	-	39	30	36	35	50	10	-	-
Truk	00	-	00	00	-	-	-49	-	-	-08	02	-12	-
Yap	05	06	00	-07	-	33	-	-	-	21	15	18	-
Koror	-	-05	00	-05	17	-	-	-06	-	-44	50	-45	-
Johnston	50	-	-	-	-	-	00	-04	00	00	-05	47	-
Majuro	-31	-	-17	-16	-13	-08	00	-07	00	00	-	-46	45
Ponape	-	44	-35	-18	-	25	05	02	00	-02	-	-45	-
Truk	00	-	-	-	-	-	08	-	00	03	05	-09	-32
Yap	-	-	-	-	-09	-	-09	-10	00	00	-	20	32
Koror	-	-	-	-30	37	-45	50	-05	00	-08	-	-	-

TABLE IV. Same as Table I, except for v 1973.

a. Coherence squares						Level (mb)							
Station	1000	850	700	600	500	400	300	250	200	175	150	125	100
Johnston	36	62	100	60	30	19	21	21	24	26	22	25	50
Majuro	14	31	100	40	13	21	11	11	14	08	10	06	16
Ponape	37	38	100	44	26	19	18	27	10	09	10	18	20
Truk	11	47	100	45	18	10	25	22	22	27	x	x	14
Yap	34	40	100	57	21	12	13	13	24	24	15	19	24
Koror	10	47	100	70	39	16	20	18	21	22	20	13	20
Johnston	18	19	24	35	56	59	85	93	100	95	85	76	60
Majuro	25	26	14	34	36	39	52	72	100	80	58	36	28
Ponape	09	25	10	23	13	38	51	71	100	87	60	33	25
Truk	24	30	22	15	14	22	55	74	100	88	x	x	17
Yap	25	10	24	24	10	09	51	70	100	84	50	08	08
Koror	14	12	21	18	14	08	48	80	100	80	41	10	09

TABLE IV. Same as Table I, except for v 1973.

b. Phase difference					Level (mb)								
Station	1000	850	700	600	500	400	300	250	200	175	150	125	100
Johnston	00	-02	00	00	05	07	06	05	05	05	08	07	08
Majuro	-13	-17	00	04	11	19	28	35	41	-	-	-	32
Ponape	00	00	00	15	32	45	-46	-40	-	-	-	-42	-48
Truk	-20	-10	00	04	16	-	-42	-39	-26	-22	x	x	-05
Yap	00	00	00	00	-11	-15	-30	-31	-26	-22	-23	-16	-15
Koror	-	06	00	-02	-07	-13	-34	-30	-33	-44	-36	-14	-05
Johnston	04	-09	-05	-07	-04	-03	-03	00	00	00	00	-03	-03
Majuro	32	25	-41	-34	-25	-17	-05	-01	00	-01	-01	-09	-08
Ponape	-	24	-	48	-32	-14	-02	00	-01	-03	-03	-03	-01
Truk	30	26	37	50	-18	-09	-05	-03	00	00	x	x	-24
Yap	26	-	26	29	-	-	00	00	00	00	00	-	-
Koror	20	35	33	31	32	-	-07	-02	00	00	03	-	-

TABLE V. Same as Table I, except for u 1973

a. Coherence squares — Level (mb)

Station	1000	850	700	600	500	400	300	250	200	175	150	125	100
Johnston	51	72	100	76	55	37	20	14	14	08	07	10	24
Majuro	18	42	100	27	23	15	04	02	04	05	05	03	18
Ponape	17	18	100	40	16	09	31	41	40	24	25	18	20
Truk	13	20	100	53	43	22	13	08	00	03	06		17
Yap	05	16	100	58	44	22	33	34	20	20	18	26	16
Koror	08	27	100	17	16	10	22	09	08	07	09	08	08
Johnston	13	12	14	18	24	34	65	88	100	92	72	53	37
Majuro	18	17	04	16	09	26	58	69	100	76	45	34	16
Ponape	19	11	40	17	09	10	40	74	100	70	46	33	12
Truk	02	13	00	06	04	15	23	61	100	73	30		14
Yap	09	18	20	13	17	32	61	82	100	88	78	43	20
Koror	44	05	08	05	04	15	19	72	100	90	59	35	18

TABLE V. Same as Table I, except for u 1973.

b. Phase difference

	Level (mb)												
Station	1000	850	700	600	500	400	300	250	200	175	150	125	100
Johnston	05	02	00	00	-02	-03	03	06	08	-	-	-	02
Majuro	-08	-07	00	02	10	02	-	-	-	-	-	-	07
Ponape	-40	00	00	04	05	-	18	14	14	08	00	05	18
Truk	-18	-04	00	04	11	17	12	-	-	-	-		13
Yap	-	00	00	07	13	18	31	34	35	35	33	24	27
Koror	00	-07	00	00	05	-	-10	-	-	-	-	-	-
Johnston	08	-05	-08	-06	-04	-05	00	00	00	00	00	00	00
Majuro	-45	-44	-	-08	-	-01	-03	-03	00	-02	-03	-02	23
Ponape	44	-20	-14	-15	-	-	03	03	00	00	-07	-07	-05
Truk	-	-30	-	-	-	08	03	00	00	00	-06		-09
Yap	-	19	00	00	05	-	-10	-	-	-	-	-	-
Koror	00	-	-	-	-	00	-10	00	00	00	00	-03	00

TABLE VI. Same as Table I, except for T, 1973

a. Coherence squares						Level (mb)							
Station	1000	850	700	600	500	400	300	250	200	175	150	125	100
Johnston	16	03	100	60	48	27	13	11	12	10	07	12	19
Majuro	52	46	100	43	06	04	25	29	07	06	17	07	22
Ponape	25	14	100	48	10	07	02	18	12	13	16	09	10
Truk	05	18	100	09	13	x	21	16	02	05	31	x	x
Yap	06	15	100	62	20	21	05	04	12	15	20	21	14
Koror	46	21	100	49	20	09	13	08	18	25	17	12	05
Johnston	08	10	12	07	08	09	13	30	100	61	31	08	11
Majuro	04	13	07	06	06	14	18	16	100	19	09	02	26
Ponape	09	11	12	10	06	10	16	09	100	29	13	07	08
Truk	10	07	02	07	03	x	03	21	100	28	06	x	x
Yap	07	09	12	09	17	12	05	06	100	91	62	52	09
Koror	13	03	18	24	27	30	04	23	100	51	21	28	13

TABLE VI. Same as Table I, except for T, 1973.

b. Phase difference

	Level (mb)												
Station	1000	850	700	600	500	400	300	250	200	175	150	125	100
Johnston	20	-	00	09	11	16	20	25	30	-	-	-11	-12
Majuro	00	03	00	00	-	-	44	48	-	-	09	-	05
Ponape	04	-04	00	05	-	-	-	12	-30	-10	-20	-	-
Truk	-	-16	00	-03	19	x	20	16	-	-	-22	x	x
Yap	-	00	00	03	00	05	-	-	-05	-05	-04	00	27
Koror	03	-04	00	-06	-20	-	48	-	05	09	-15	-10	-
Johnston	-	-	-30	-	-	-	14	03	00	-05	-16	-	48
Majuro	-	96	-	-	-	00	18	00	00	-02	-	-	45
Ponape	00	14	30	-	-	-	-10	-	00	02	-15	-	-
Truk	-	-	-	-	-	x	-	-04	00	-03	-	x	x
Yap	-	-	05	-	08	00	-	-	05	09	-15	-10	-
Koror	-10	-	-05	-12	-19	-32	-	00	00	-09	-09	-22	-20

downward in this layer, than a reversal between 300 and 100 mb. The structure at Koror is much like that at Yap as might be expected in view of their proximity.

C. VERTICALLY AVERAGED SERIES SPECTRA

The foregoing results lead the author to utilize a vertical-averaging scheme to significantly reduce the number of time series to be analyzed yet still retain the character of the data for most of the individual levels. This was done despite the phase tilts in 1973 because the scheme is designed such that the phase difference between levels to be averaged is $< \frac{1}{5}$ of a cycle. Table VII outlines this scheme which is applied to all stations except Johnston Island. The wind components are divided between two layers of opposite phases and averaged within each layer. Three temperature series are used. T_2 represents the temperature between the two layers whereas T_1 is representative of the temperatures near the tropopause and T_3 near the surface. Relative humidities were averaged for the 700-400 mb layers because Wallace (1971) and Gray, et al (1975) have found that fluctuations in the relative humidity data are much more pronounced above 700 mb.

The power spectra for the layer quantities u_L, v_L, u_H, v_H, T_1, T_2, T_3 and RH are presented in Figs. 5a-c for 1972 and Figs 5d-f for 1973. As was expected the v_L and v_H spectra are characterized by significant peaks in the 4-5 day period at many stations for both years. Related peaks for u_H exist at all stations in 1972 and at all stations except Truk in 1973. There is some evidence of related peaks in the u_L spectra, especially in 1973, but most of the power is found in the

TABLE VII. Scheme for vertical averaging.

Parameter	Symbol	Levels Averaged
Meridional wind component (lower levels)	v_L	1000,850,700,600 mb
Meridional wind component (upper levels)	v_H	300,250,200,175,150,125 mb
Zonal wind component (lower levels)	u_L	1000,850,700,600 mb
Zonal wind component (upper levels)	u_H	300,250,200,175,150,125 mb
Temperature	T_3	1000,850 mb
	T_2	300 mb
	T_1	125-100 mb
Relative humidity	RH	700,600,500,400 mb

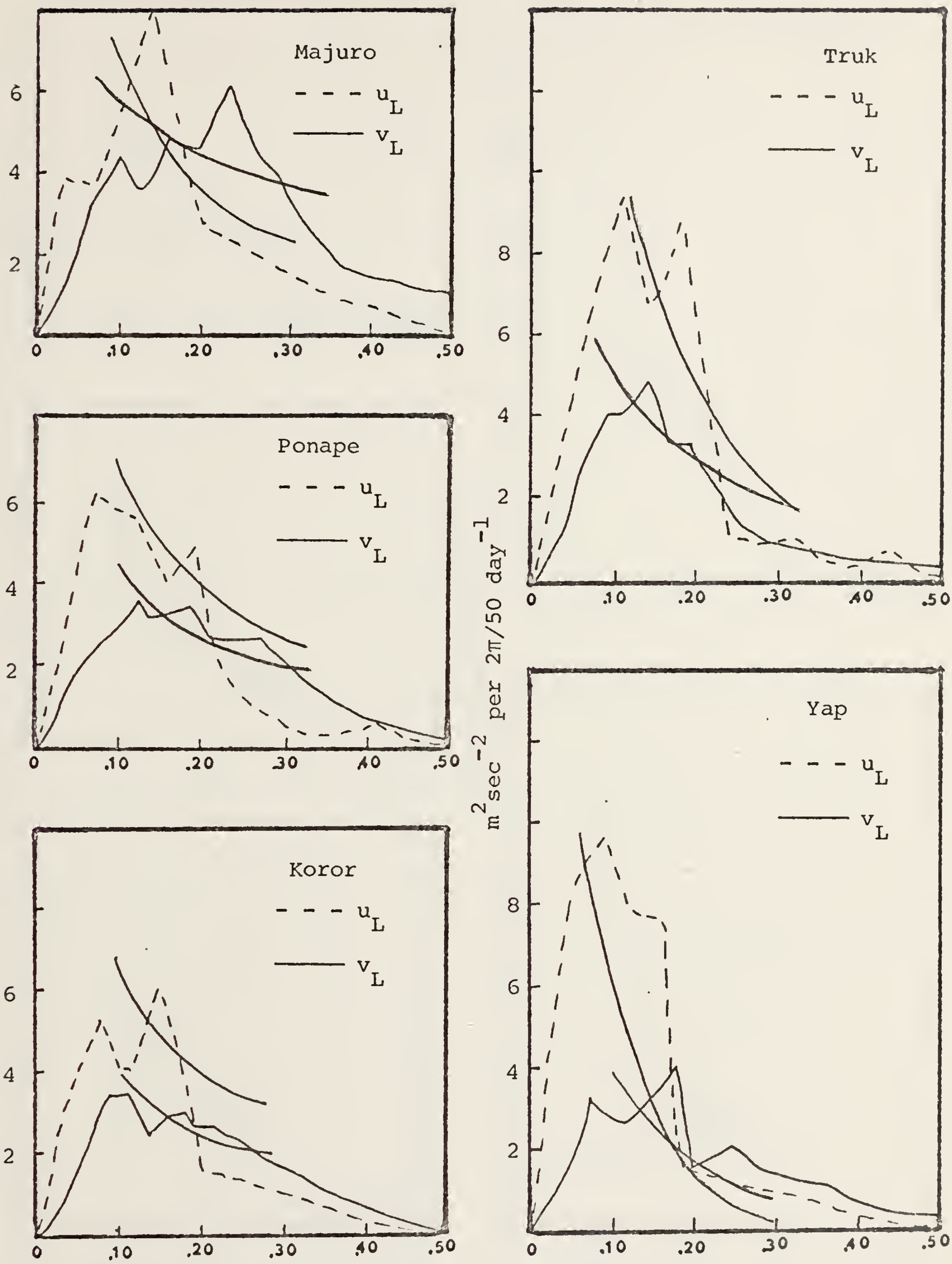


Figure 5(a). Power spectral estimates for the vertically averaged series v_L and u_L zonal and meridional wind components for 1972. Units are in $m^2 sec^{-2}$ per $2\pi/50$ day^{-1}.

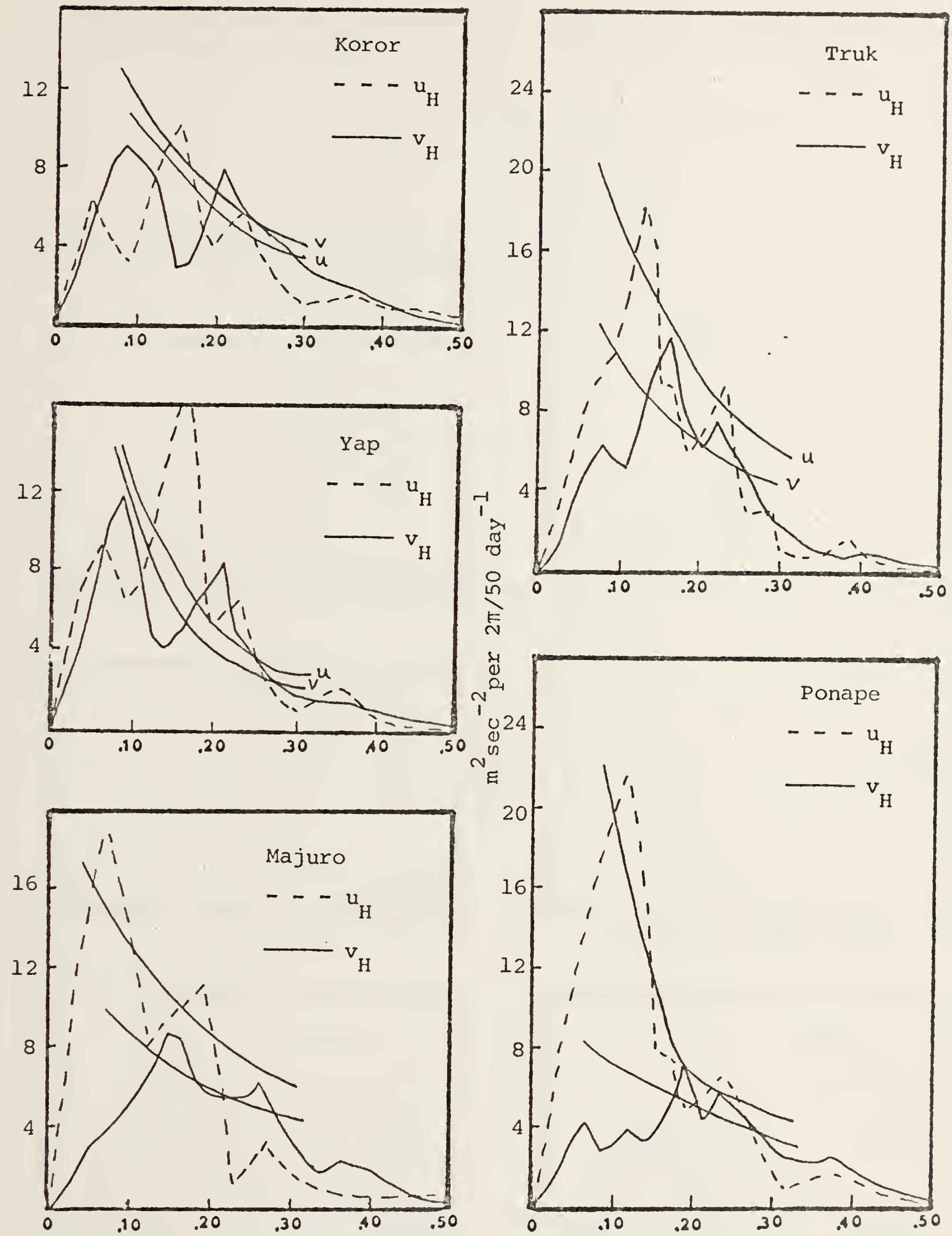


Figure 5(b). Power spectral estimates for the vertically averaged series v_H and u_H zonal and meridional wind components for 1972.

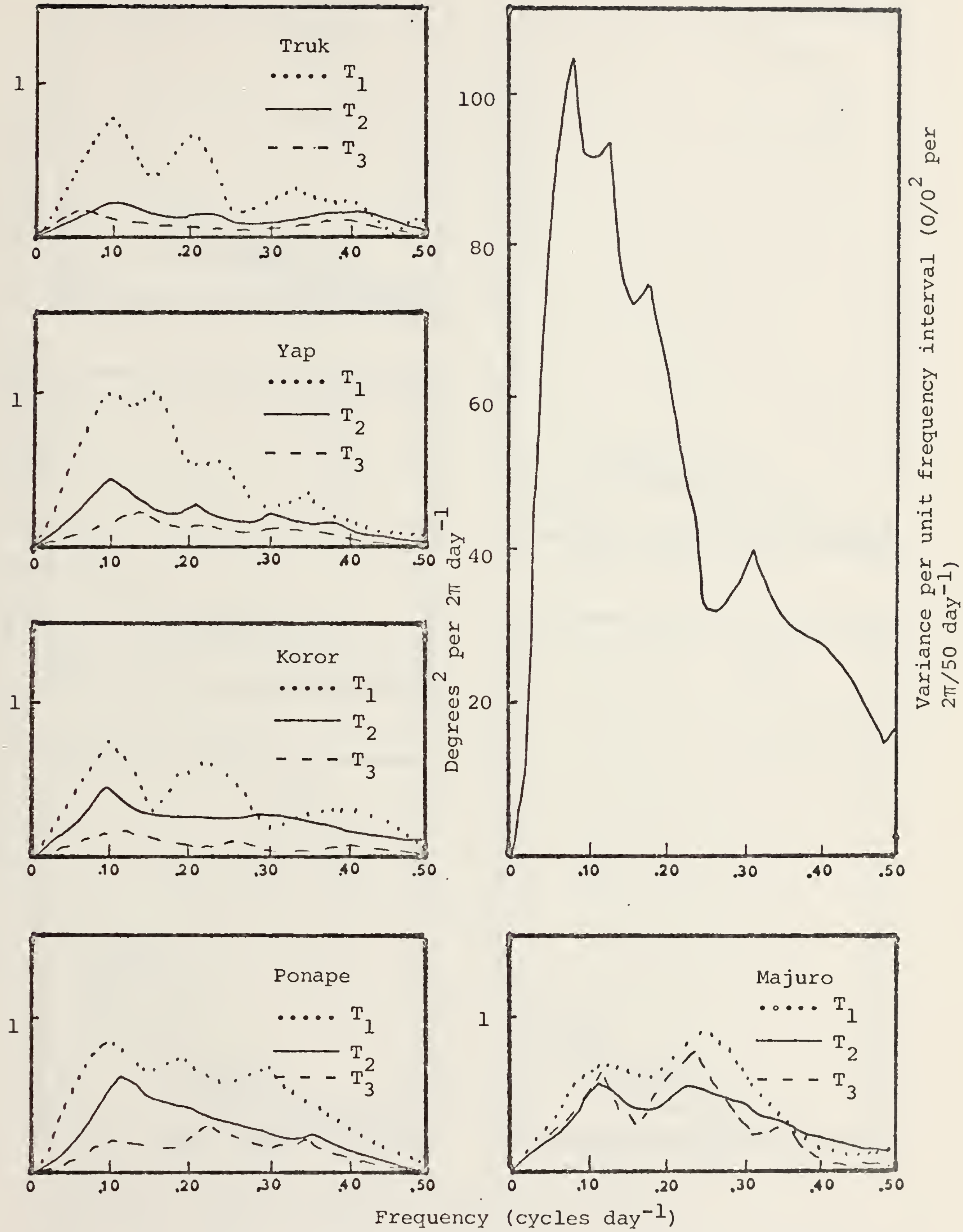


Figure 5(c). Power spectral estimates for the vertically averaged series T_1, T_2, T_3 and composite power spectral estimate for RH for all stations except Johnston Island for 1972 period.

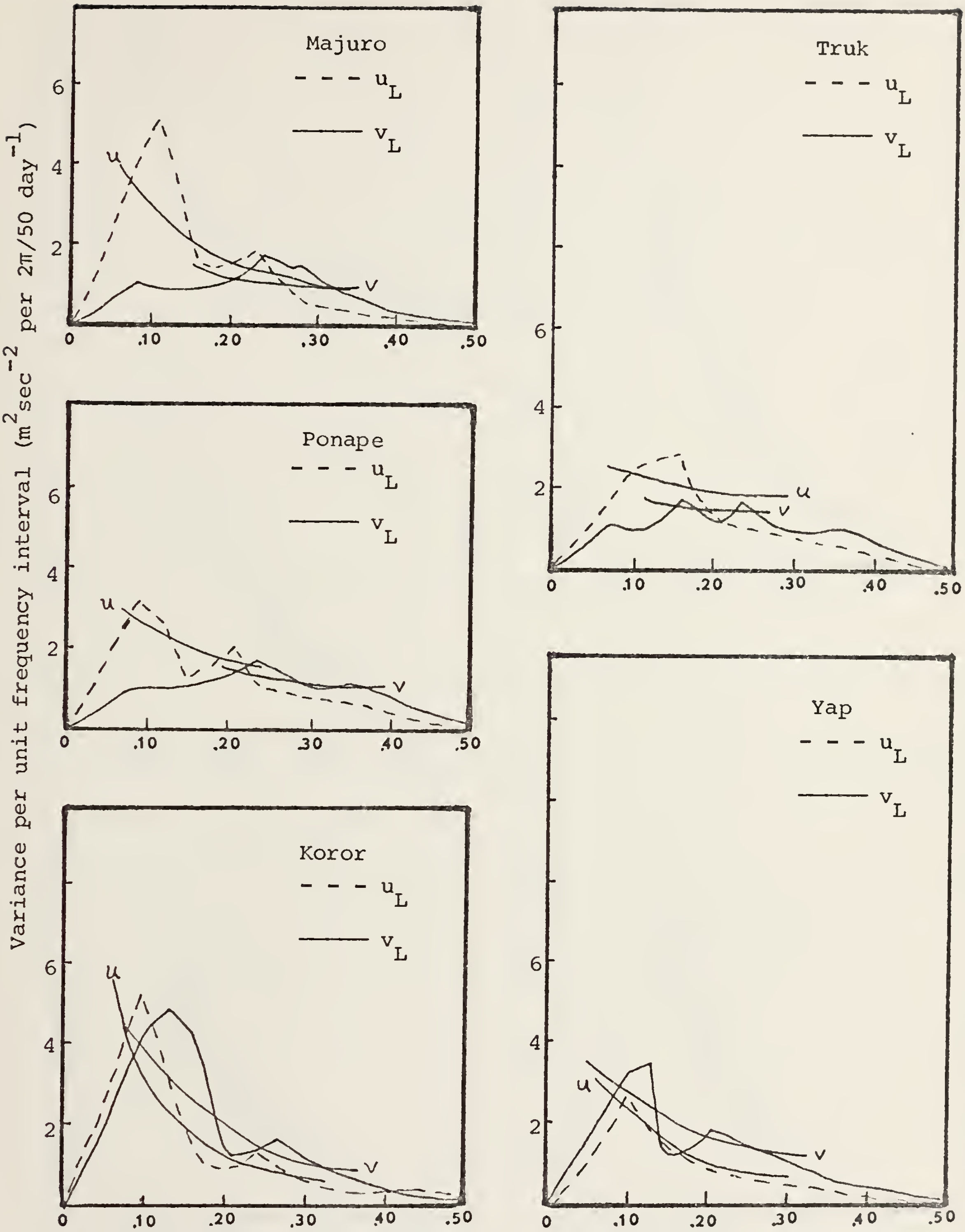


Figure 5(d). Same as Fig. 5(a), except for 1973.

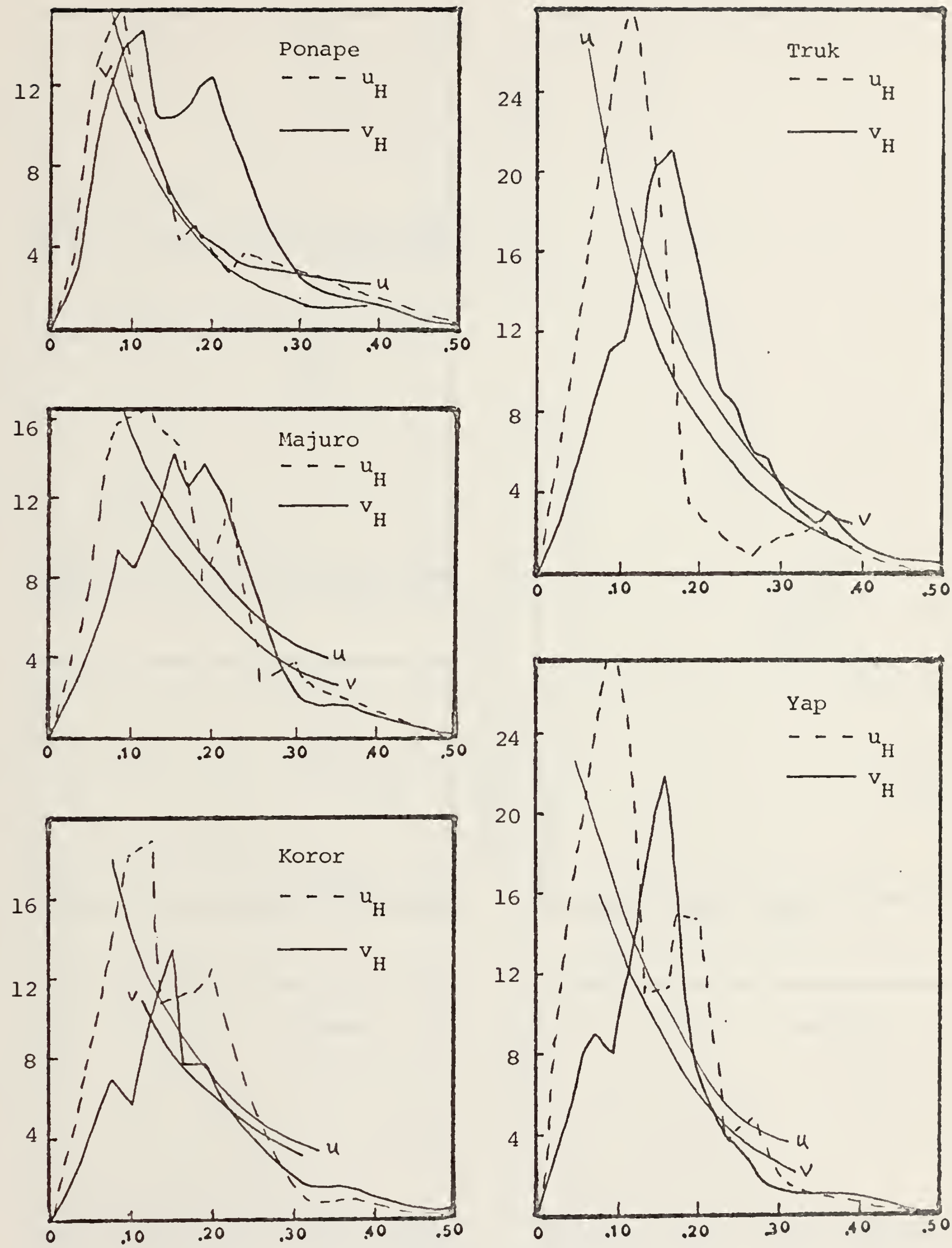


Figure 5(e). Same as Fig. 5(b), except for 1973.

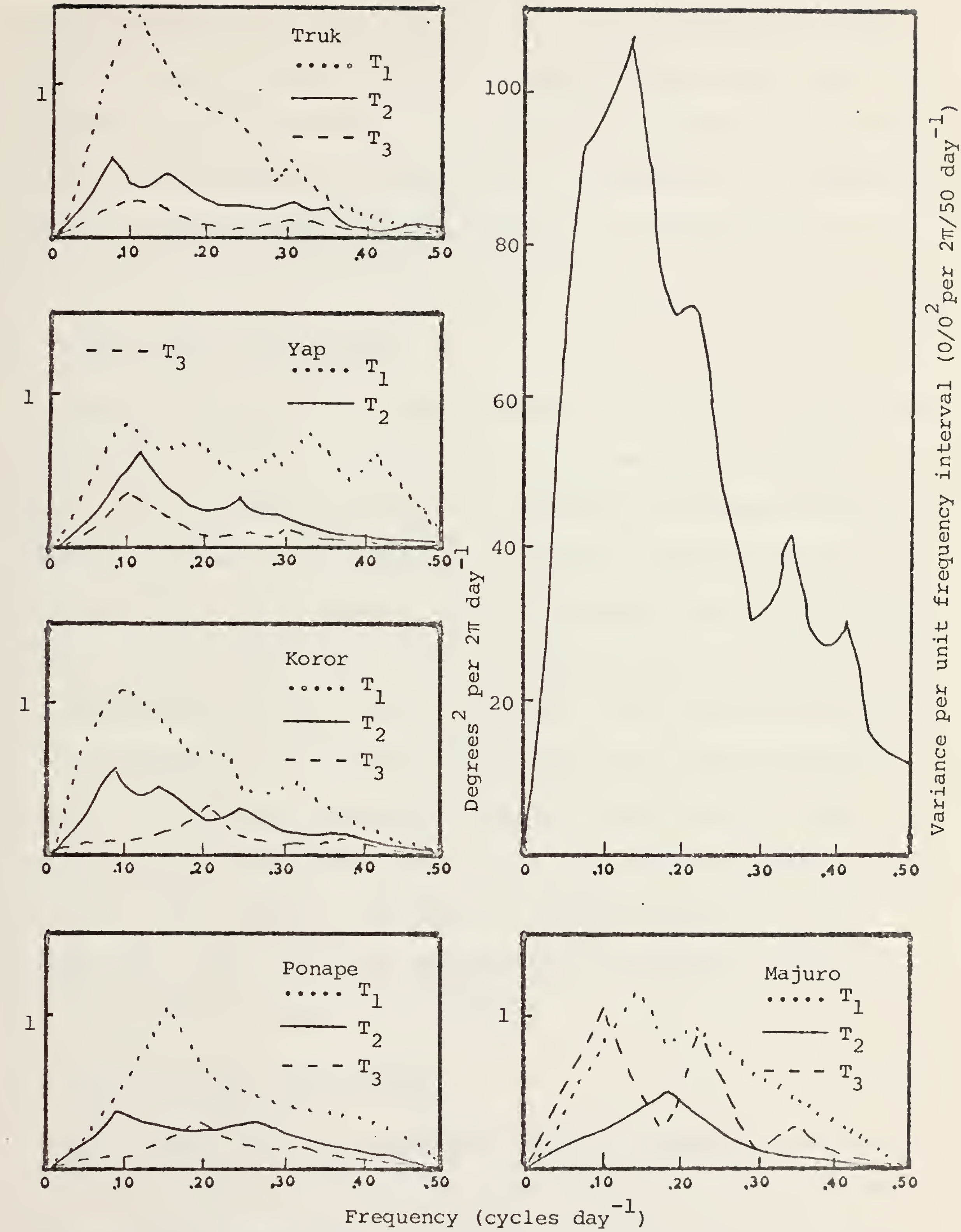


Figure 5(f). Same as Fig. 5(c), except for 1973.

lower frequencies near 0.10 cpd. It is also noted that more prominent spectral peaks of the 1973 v_H series also exist at somewhat lower frequencies centered around 7-10 days, and sometimes these peaks cover a wide band which include the 4 to 5 day periods. The power spectra for RH show a small peak in the 4-5 day range for both years. The spectra for T are generally quite flat but tendencies for peaking in the 4-5 day period can still be detected at many stations.

D. INTER-STATION CROSS SPECTRA

Inter-station cross spectra were computed for the 0.18-0.24 cpd frequency band of v_L and v_H for both years. The results are presented in Figs. 6 and 7 as phase-differences vs longitudinal difference between stations. For each pair of stations the eastern station was used as the base series. It is apparent from these figures that the waves propagate westward in both layers during both years since the phase of the eastern stations leads those further west. The wavelengths for the wave disturbances is estimated by the intersection of the best-fitting line of the points with significant coherence squares and the unit cycle phase line. For 1972 the wavelengths are seen to be about 3500 km for both v_L and v_H and for 1973 3900 km and 3450 km for v_L and v_H, respectively. This is in good agreement with the results of Wallace and Chang (1969) and Chang, et al (1970).

E. INTER-PARAMETER CROSS SPECTRA

Cross spectra were computed between the light vertically-averaged layer quantities to determine the structure of the 4-5 day waves. The results of these computations are tabulated in Table VIII for 1972 and Table IX for 1973.

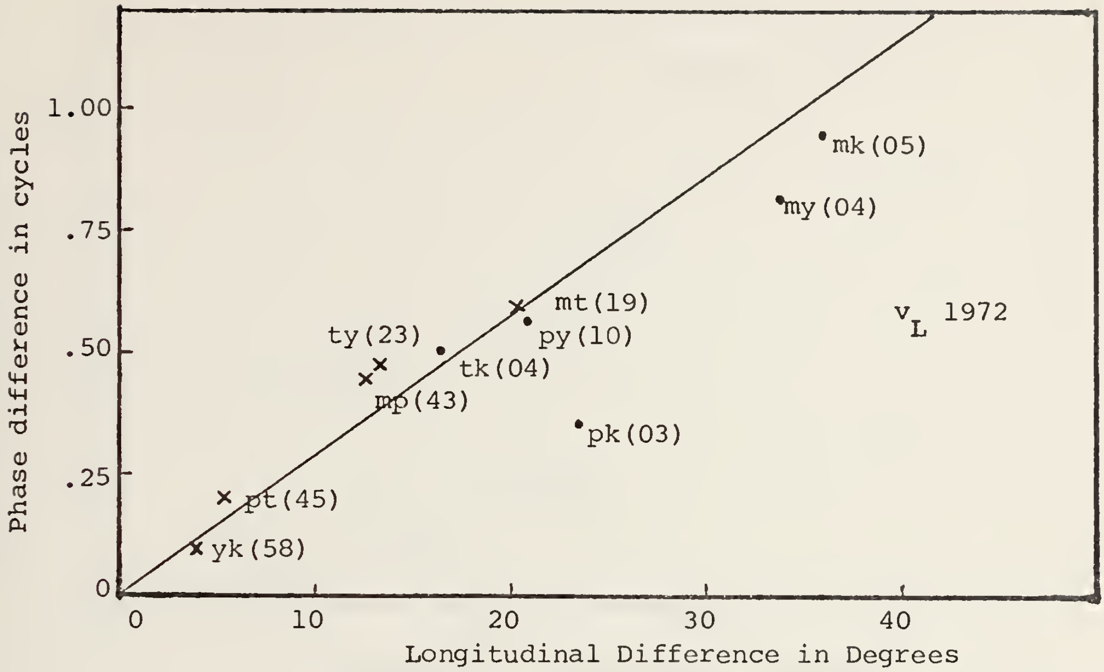
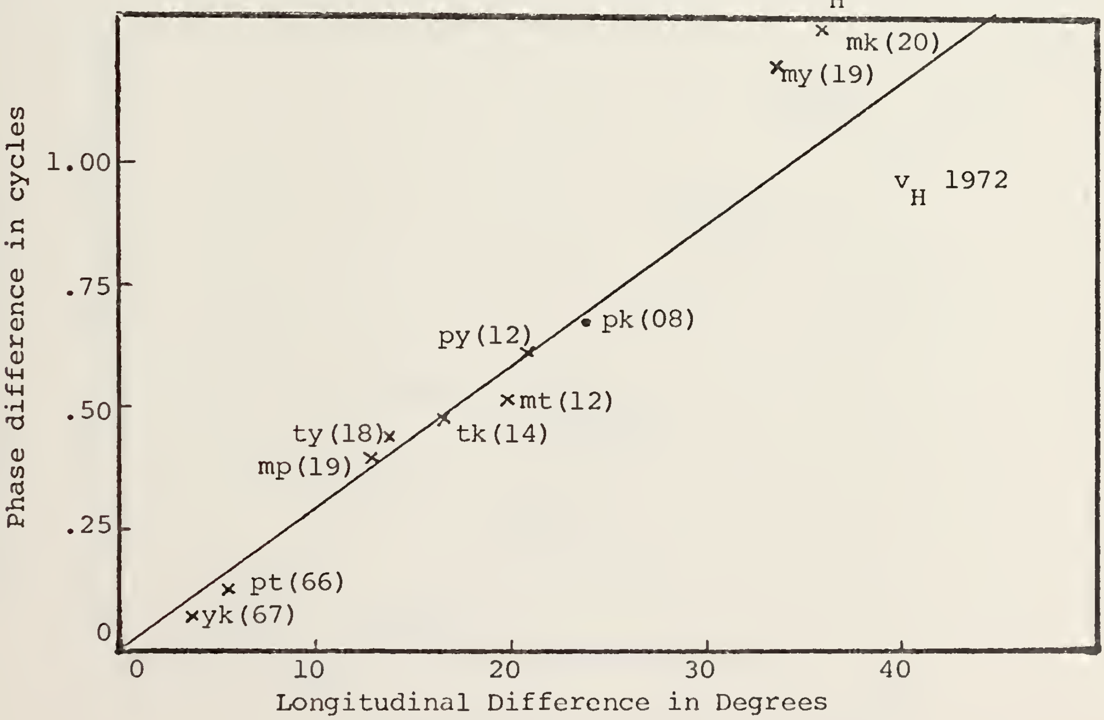


Figure 6(a). Phase difference in cycles between v_L fluctuations in the 0.18-0.24 cpd frequency bands vs longitude difference between stations for 1972. Data points are labeled with the identifiers (M: Majuro, P: Ponape, etc.) for the station pair involved. Longitude difference is measured from the first station westward to the second. Phase difference is plotted as the amount by which the fluctuations of the first station lead those of the second. Coherence square values are plotted next to the data points with crosses denoting coherence square values $\geq$ .11, the 95% significance level.

Figure 6(b). Same as Fig. 6(a), except utilizing the v_H series for 1972.



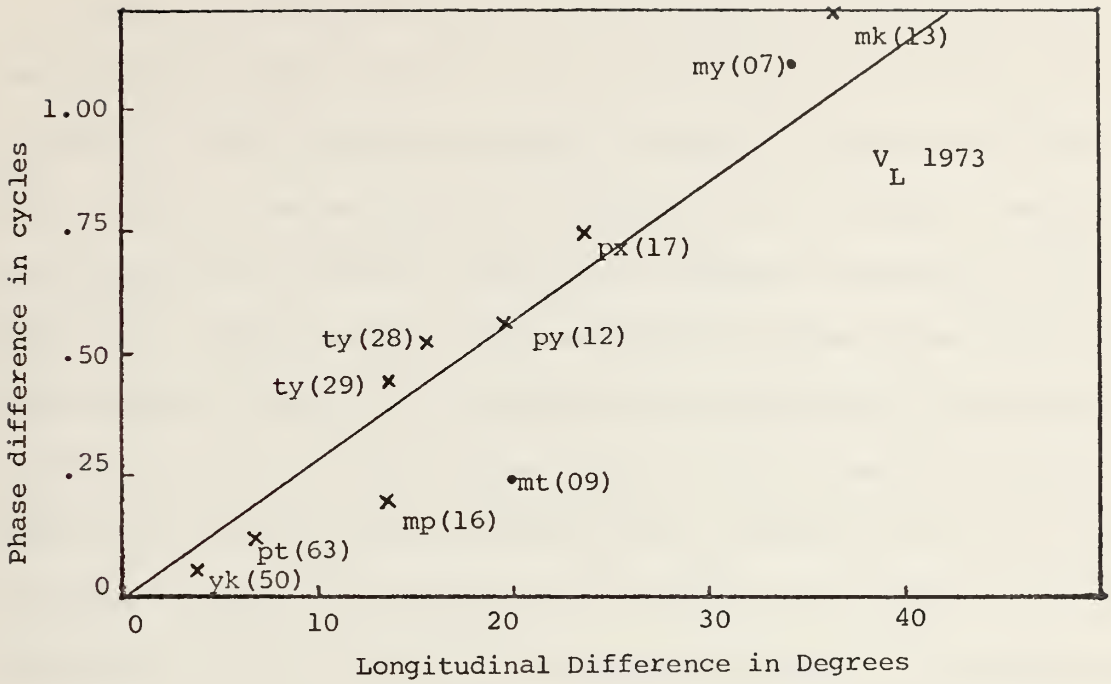
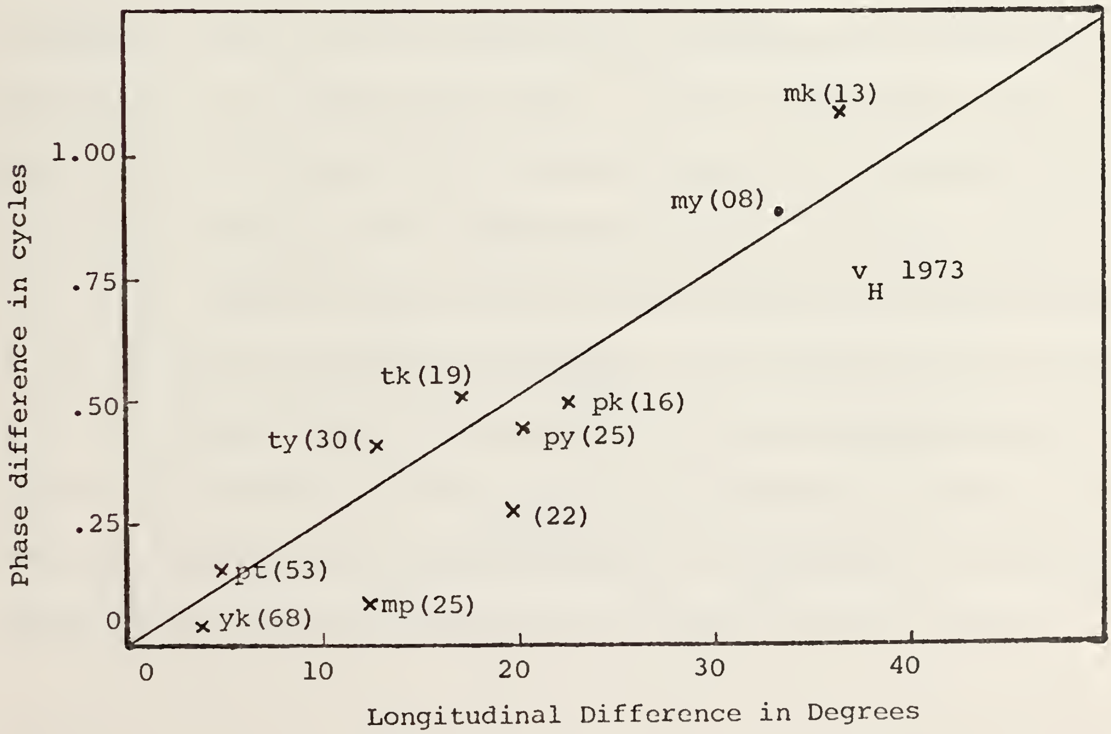


Figure 7(a). Same as Fig. 6(a), except utilizing the V_L series for 1973.

Figure 7(b). Same as Fig. 6(b), except utilizing the v_H series for 1973.



Cross spectra between v_L and v_H as expected have significant coherence square values and are out of phase by between 1/3 and 1/2 of a cycle in 1972. For 1973 the phase is typically closer to 1/3 of a cycle except at Majuro where it is half-cycle out of phase. However, the interpretation of these results are different from that of the 1972 season because of the phase propagation noticed in the inter-level cross spectra. The u_L and v_L series are significantly correlated as indicated by the coherence values during the 1972 season. They are generally in phase except at Majuro where v_L leads u_L by 1/3 of a cycle. The phase relationships between these parameters for 1973 is much less definitive. Also in 1972 the cross spectra between v_L and temperatures show v_L lags the middle tropospheric temperature fluctuations, T_2, by about 1/3 of a cycle at all stations where the coherence squares exceed the confidence limits and leads the low-level temperature fluctuations, T_3, by about 1/4 to 1/3 of a cycle. This is in excellent agreement with the results of Chang, et al (1970). It can be inferred that the troughs are cold near the surface and are capped by warm temperature anomalies in the middle-upper levels. Direct cross spectra also indicate that T_3 is out of phase with T_2 while it tends to be in phase with T_1. So near the tropopause the temperature above the low-layer trough is cold. This thermal structure plus the out-of-phase relationship between lower and upper layers are in agreement with the gradient wind relationship and indicate that the waves of 1972 are equivalent-barotropic in nature. In 1973 most of the v_L-T_2, v_L-T_3 coherences are quite low and the few significant phase relationships are inconsistent, although the phase reversal between T_1 and T_2 and T_2 and T_3 is still evident.

The phase between v_L and RH varies widely in 1972. At the two easternmost stations, Majuro and Ponape, v_L leads RH slightly while it lags RH by 1/3 of a cycle at Yap. This is somewhat surprising because at Majuro and Ponape the maximum of RH fluctuations is slightly to the east of the maximum of v_L, or in the western end of the ridge area. The result at Yap is more closely in agreement with those of Chang, et al (1970) which places maximum RH in the trough. The results for 1973 show that at Majuro and Koror the RH maxima are in the troughs while at Ponape and Truk they are in phase with maximum v_L. There is no good explanation for these diverse results. The composite RH spectra depicted in Figs. 5(c) and (e) show quite indistinct peaks near the 4-5 day periodicity which may somewhat downplay the significance of the RH-v_L relationship. This relationship tends to support the structure with maximum RH being placed in the trough. However, because RH is temperature-dependent, it may not be a very good humidity parameter for the analysis. Perhaps in future studies of this nature specific humidities may be calculated from the RH values before analysis is further attempted.

The cross spectra with v_H as the base series produces no surprising results. Where the coherence squares between v_H and u_H are significant they tend to be nearly in phase. In 1972 at the three stations where the coherences are significant v_H lags T_1 by 1/4 of a cycle. This is true at all stations in 1973. These results are consistent with those discussed earlier. The RH-T_3 relationships are very similar for both years. The coherence squares are always high and the phases uniformly opposed.

The relationships given in Tables VIII and IX, together with those extracted from Tables I-VI, suggest different schematic depictions for the waves. Figure 8 illustrates the scheme for 1972. Figure 9(a) represents the scheme for 1973 at Majuro, Ponape, and Truk while Fig. 9(b) represents the scheme for the two westernmost stations, Yap and Koror. The distribution of RH is not incorporated due to the inconclusive results.

TABLE VIII. Inter-parameter cross spectra results for the .18-.24 cycle day^{-1} frequency bands at each station except Johnston for 1972.

a. Coherence square. Significance level $\geq$ 95% if coherence^2 $\geq$ .11.

	Base series: v_L					Base series: v_H			Base series: T_3		
Station	v_H	u_L	T_2	T_3	RH	u_H	T_1	T_2	T_2	T_1	RH
Majuro	15	13	29	21	20	06	31	09	25	27	15
Ponape	13	44	10	11	17	13	08	06	26	11	05
Truk	09	44	23	05	04	22	07	17	03	11	13
Yap	19	12	13	21	14	11	35	05	11	07	15
Koror	12	23	19	08	04	04	31	21	13	23	27

b. Phase difference in cycles. Positive values indicate the base series leads other series.

	Base series: v_L					Base series: v_H			Base series: T_3		
Station	v_H	u_L	T_2	T_3	RH	u_H	T_1	T_2	T_2	T_1	RH
Majuro	-29	34	-20	34	10	-	-24	-	50	-23	47
Ponape	-39	04	-	15	08	-06	-	-	36	-26	-
Truk	-	00	-40	-	-	-12	-	40	-	-12	-33
Yap	-40	08	-44	20	-31	25	-20	-	-45	-	46
Koror	50	07	-26	24	-	-	-23	46	-40	-08	50

TABLE IX. Same as Table 8, except values are for 1973.

a. Coherence square

	Base series: v_L					Base series: v_H			Base series: T_3		
Station	v_H	u_L	T_2	T_3	RH	u_H	T_1	T_2	T_2	T_1	RH
Majuro	12	08	20	19	12	04	15	07	13	18	40
Ponape	19	24	12	09	22	19	28	15	11	04	11
Truk	32	08	09	09	16	15	28	09	11	11	15
Yap	18	12	04	07	05	14	23	08	16	19	34
Koror	30	15	05	23	24	09	13	11	03	21	28

b. Phase difference in cycles.

	Base series: v_L					Base series: v_H			Base series: T_3		
Station	v_H	u_L	T_2	T_3	RH	u_H	T_1	T_2	T_2	T_1	RH
Majuro	50	-	-36	18	-18	-	-25	-	31	-06	46
Ponape	-35	37	10	-	03	-12	-13	40	-33	-	43
Truk	-35	-	-	-	03	-11	-21	-	48	-05	-36
Yap	-24	04	-	-	-	-09	-23	-	40	04	49
Koror	-31	-17	-	05	-29	-	47	14	-	-12	-43

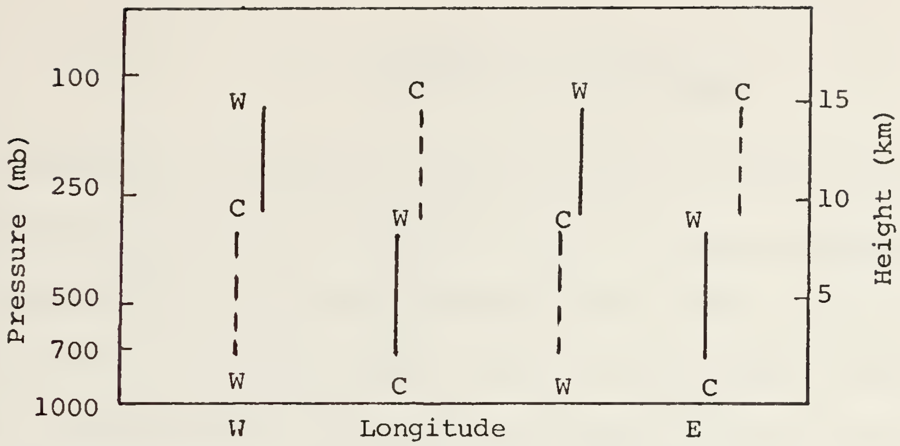


Figure 8. Schematic zonal cross section through the observed wave disturbances for 1972 in the Western Pacific. The solid lines represent troughs and the dashed lines ridges. The letters C and W indicate respectively negative and positive temperature anomalies.

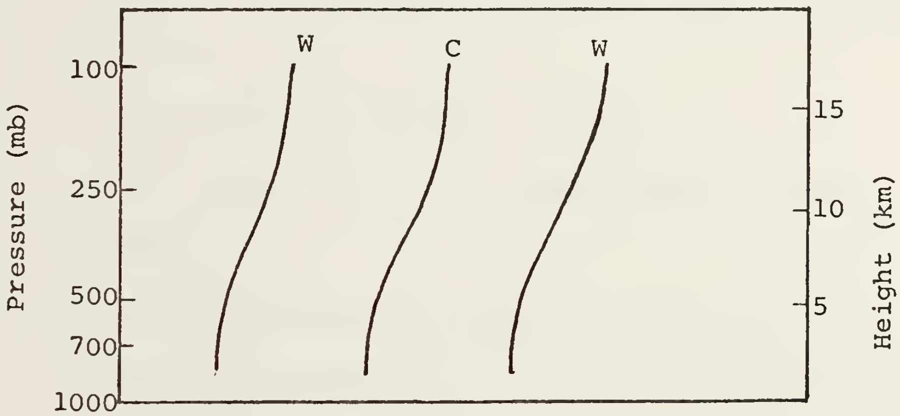


Figure 9(a). Same as Figure 8, except for Truk and stations further east for 1973.

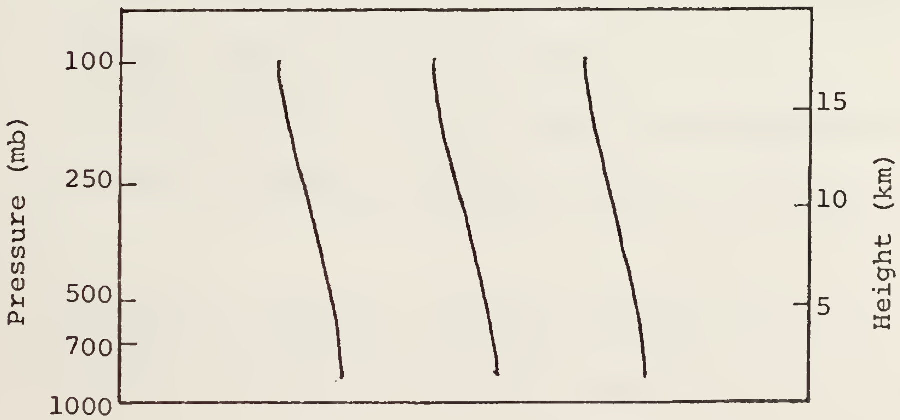


Figure 9(b). Same as Figure 9(a), except for Yap and Koror.

IV. SUMMARY AND CONCLUSIONS

The spectrally determined wave structures of 1972 and 1973 show some similarities between the two years as well as some differences. Since Johnston Island has a different dominant periodicity with significant coherences in the 7-10 day range, which may represent a different type of wave disturbance, it will be excluded from the following discussion. The main similarities at the other five stations between 1972 and 1973 are:

1. The periods of the waves are in the 4-5 day range at all tropical stations.

2. The wavelengths are close to 3500 km.

3. A general out-of-phase relationship exists between low and high level v-components.

The main differences between the two periods are:

1. No significant vertical tilt exists for the waves in 1972. This is contrasted with a substantial eastward tilt with height in 1973 for the waves at the easternmost stations, Majuro, Ponape and Truk. At the western stations, Koror and Yap, the 1973 waves tilt westward with height, and at a somewhat larger slope than in 1972.

2. The thermal structure of the waves is well-defined with a warm core in the middle troposphere, whereas in 1973 it is quite poorly-defined.

3. As depicted in Table X, the power densities of the low level waves (below about 300 mb) are everywhere higher in the 1972 period as

Level (mb)	Station KOROR	1972 YAP	TRUK	PONAPE	MAJURO	JOHNSTON
100	28	2.7	4.1	4.8	6.7	10.2
125	6.9	6.6	11.2	(15.8)	8.6	21.0
150	9.9	10.6	16.4	(13.8)	9.0	39.5
175	10.6	13.3	14.5	9.5	11.7	51.6
200	9.6	15.1	(12.5)	4.8	8.4	50.6
250	7.5	(14.0)	9.0	4.6	6.4	38.1
300	(7.7)	(8.1)	(8.8)	6.0	5.0	25.3
400	(7.6)	(7.7)	(11.2)	(6.9)	(6.5)	15.6
500	(5.6)	(6.4)	(9.6)	(8.4)	(9.0)	9.9
600	(4.6)	(5.5)	(6.1)	(8.0)	(9.0)	(7.2)
700	(4.1)	(3.6)	(3.8)	(5.4)	(6.7)	(4.7)
850	(2.6)	(3.1)	(4.4)	(3.4)	(6.2)	(2.1)
1000	(1.1)	(1.5)	(2.3)	(0.9)	(1.9)	(1.3)

TABLE X(a). Representation of the v power densities averaged over the .18-.24 cpd frequency bands (.08-.14 for Johnston) at each station for each of the 13 levels studied (1000-100 mb) for 1972. Units are m^2 sec^{-2} per $2\pi/50$ day^{-1}. Figures in brackets are higher than the corresponding figures for 1973. See Table X(b) below.

Level (mb)	Station KOROR	1973 YAP	TRUK	PONAPE	MAJURO	JOHNSTON
100	(4.5)	(3.6)	(5.3)	(7.7)	(6.9)	(15.6)
125	(14.4)	(8.6)	x	8.9	(11.9)	(32.7)
150	(10.4)	(16.0)	x	11.9	(14.3)	(47.6)
175	(15.4)	(20.6)	(17.5)	(11.7)	(13.8)	(67.5)
200	(13.5)	(17.0)	12.1	(12.7)	(11.9)	(80.9)
250	(7.7)	9.7	(10.2)	(9.8)	(8.2)	(70.3)
300	5.4	7.5	5.2	(7.3)	(7.9)	(51.2)
400	2.6	3.3	3.9	3.5	5.7	(29.5)
500	1.8	3.1	2.3	2.0	5.5	(11.8)
600	3.0	2.5	2.4	1.3	3.7	6.3
700	2.2	2.3	2.1	1.5	2.4	3.6
850	2.0	2.7	2.2	1.9	1.2	2.0
1000	0.9	1.3	1.7	0.8	0.9	0.9

TABLE X(b). Same as Table X(a), except for 1973.

compared to the 1973 period. Above about 300 mb this is reversed with the densities being greater in the 1973 season. The figures presented in Table X may also be converted to the approximate wave amplitudes by taking the square root of the value given. This is possible because the factor required to yield amplitudes from the values in Table X (prior to taking the root) is close to unity.

The lack of vertical tilt and the better-defined thermal structure in 1972 suggests that the waves are more dominated by the "warm-core" energetics in this year. This seems to be a direct affect of the warmer SST which favors cumulus convection and latent heating. Due to the prominence of this energy source one may expect that the waves would be more active in 1972. This is indeed the case at the lower and middle levels below 300 mb. It may be due to this larger wave amplitude at the lower levels that the year of 1972 has a very active typhoon season (based on the CISK theory which emphasizes the importance of low-level convergence).

The structure of the waves may also be influenced by the environmental mean flow. Figure 10 is a longitude-height section of the 8-month mean zonal wind in the two seasons. It is evident that much stronger westerly shear in the vertical exists in 1973. This may be related to the position and intensity of the Walker Circulation due to the cold SST anomalies in the eastern Pacific. The differences in the mean flow patterns are most pronounced in the upper troposphere, and Holton's (1971) numerical model suggests that vertical shear has an important effect in the wave structure. It is thus reasonable to assume that the difference in vertical phase structure and the upper-level amplitudes is primarily due to the difference in the mean flow.

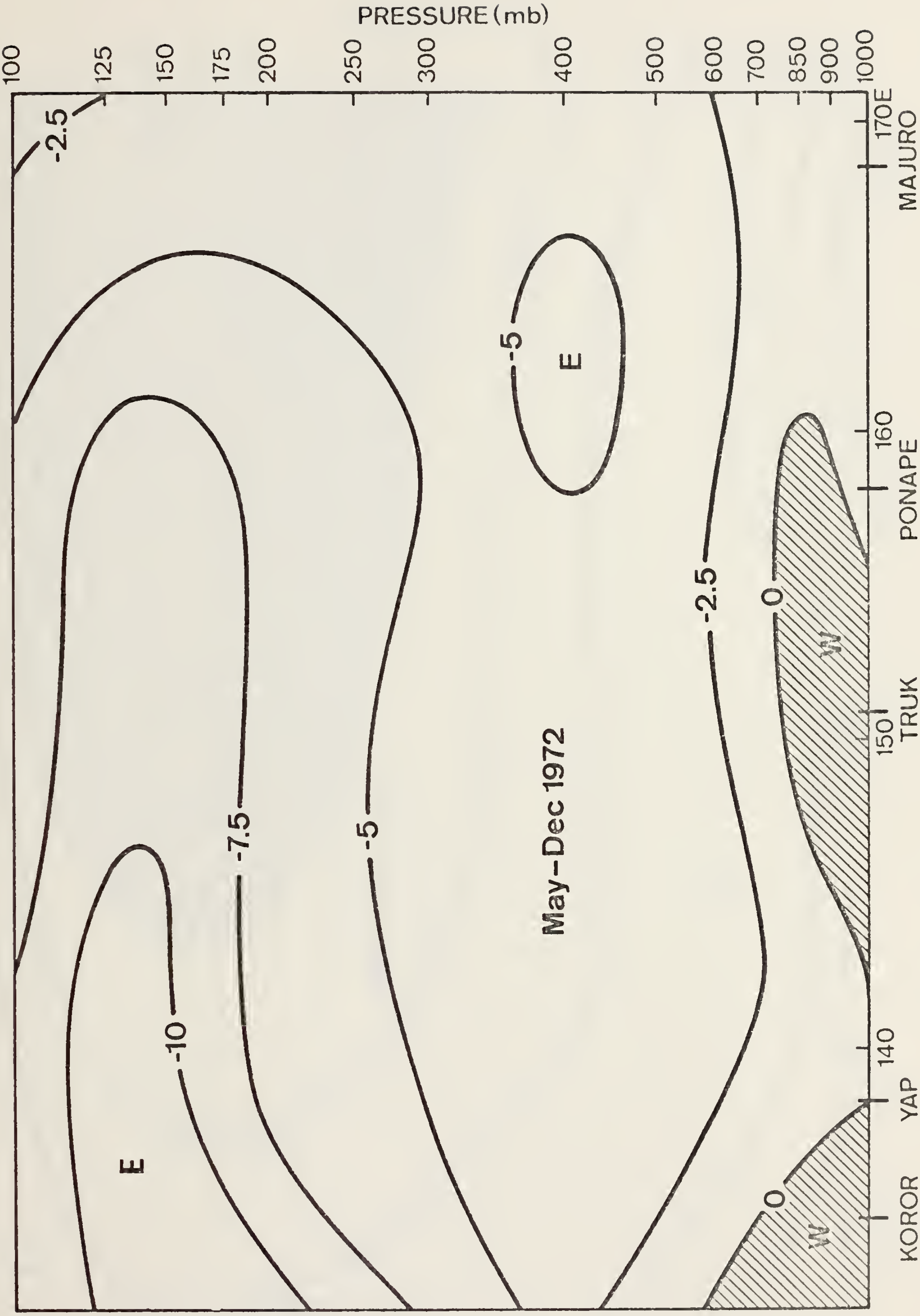


Figure 10(a). Mean u profile over the western Pacific Ocean for May-December 1972.

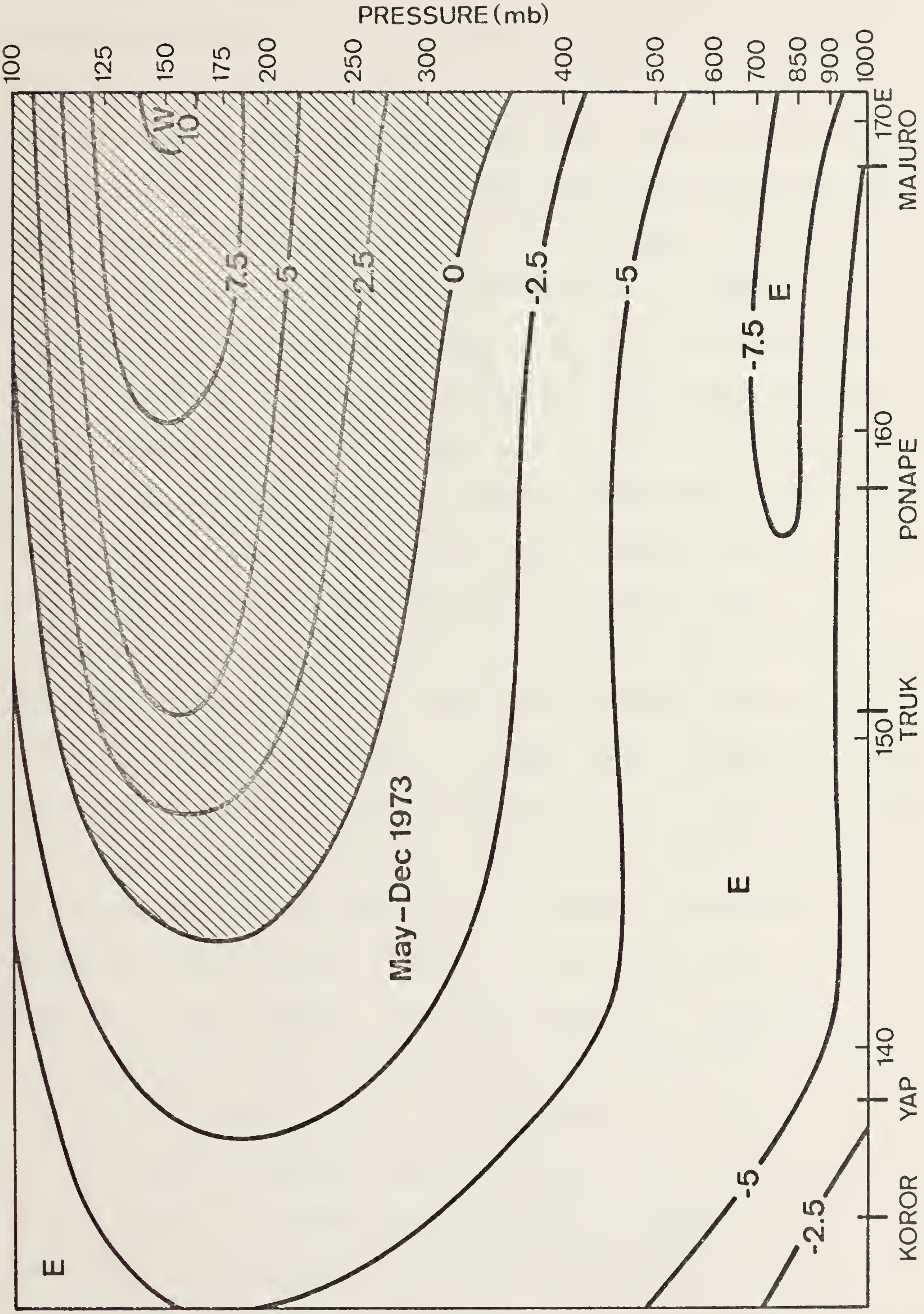


Figure 10(b). Same as Fig. 10(a), except for 1973.

The three eastern stations, Majuro, Ponape and Truk have strong eastward phase tilt from lower to upper troposphere in 1973. This is consistent with Holton's (1971) calculations for a strong vertical westerly shear of mean zonal wind with height. At Yap and Koror both years have weak easterly shear and the waves tilt westward with height. This is again in agreement with Holton (1971); however, the 1973 shear is even weaker than in 1972, while the phase tilt is larger. An explanation for this apparent paradox is that the 1972 waves are much more convectively controlled, as indicated by the warm core structure. It is reasonable then to expect that such waves have less vertical tilt.

The larger amplitudes at upper levels in 1973 may be indicative of the presence of energy sources other than condensation heating. Among the possibilities are dynamic instability and mid-latitude forcing. The strong westerlies over the eastern stations suggest that the tropical upper tropospheric trough (TUTT) may be extended equatorward from its usual position in the Pacific. Sadler (1967) and others have found that upper-level synoptic-scale disturbances tend to develop along TUTT, and dynamic instability has been proposed as a possible mechanism (Krishnamurti, 1971 and Colton, 1973). Classical wave theory also suggests that mid-latitude forcing is more efficient when the zonal mean flow is more westerly. These mechanisms may be responsible for the upper-level waves which occupy a wide spectral band of variance including the 7- to 10-day and the 4- to 5-day bands.

The very quiet typhoon season of 1973 may be due to a combination of two factors. The colder SST certainly are unfavorable for warm core development. In addition, the strong vertical wind shear, which is itself a consequence of the SST distribution, tends to suppress tropical

storm development due to the ventilation effect (Gray, 1975).

The above discussions suggest that the two possible effects of SST variations on waves, mentioned in the introduction, namely the direct control of cumulus heating as an energy source and the indirect influence through planetary-scale circulation changes, are both present. However, these conclusions can only be considered tentative until a larger sample of contrasting SST anomaly periods are studied. Also SST data in the western Pacific for the two years of the present study were not available to the author. The above conclusions can be re-examined and further refined when they are available. In any case, it would be desirable to expand the present study to other years.

Finally, the estimated wavelengths in both upper and lower troposphere during both years are close to 3500 km. This result indicates that the presence of vertical phase tilt does not itself dictate the existence of a different type of wave disturbance with a longer wavelength on the order of 8000 km, as was suggested by Wallace (1971).

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